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LANGUAGE AND LITERACY FROM A
COGNITIVE NEUROSCIENCE PERSPECTIVE

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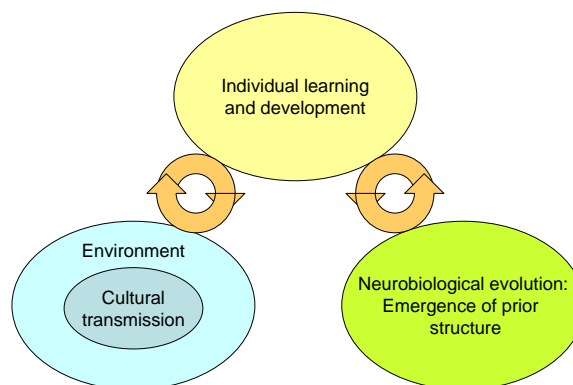Karl Magnus Petersson, F.C. Donders Centre for Cognitive Neuroimaging

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INTRODUCTION

This chapter consists of two parts. The first part presents a general perspective on cognitive neuroscience where we use natural language as an example to illustrate various issues involved in understanding the (human) brain from a cognitive point of view. We start with a brief review of some relevant structural and functional facts about neural systems and an outline of the cognitive science perspective on psychological explanation. A common framework for describing cognitive systems is Marr's three levels of analysis: the computational, the algorithmic, and the implementation level (Marr, 1982). As a first approximation, natural language can be viewed as analyzed at the levels 1 – 3 in theoretical linguistics (e.g., Sag, Wasow, & Bender, 2003), psycholinguistics (e.g., Gernsbacher, 1994), and neurolinguistics (e.g., Brown & Hagoort, 1999), respectively.

Cognitive neuroscience typically works with a modified perspective on cognition, learning, and development compared to classical cognitive science, although the underlying ideas are essentially similar. Within this modified framework, the three descriptive levels can be generalized to: 1) the *cognitive level* - a formal theory of structured cognitive states and the cognitive transition system, which specifies the transitions between cognitive states and the results of information processing; 2) the *dynamical system level* - given a formal cognitive theory, a state-space is specified and processing is formulated in terms of a dynamical system which embeds the system specification at the cognitive level; 3) the *implementation level* - given a dynamical system, this level specifies the physical hardware implementation of the dynamical system, for example a neural network (Haykin, 1998; Koch & Segev, 1998).

[Figure 1]

In the following, we will integrate this perspective with some contemporary ideas on the functional architecture of the human brain, learning and adaptation at different time-
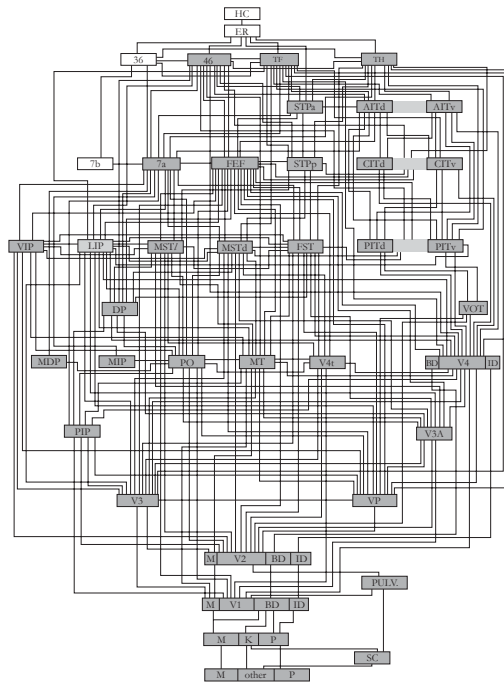
scales, and more broadly the interaction, via individual learning, between factors determined by neurobiological evolution and the environment of the (human) cognitive system (including social and cultural transmission; cf., **Figure 1**). This first part serves as a background to the second part of the chapter and provides a glimpse of the challenges that the human brain poses to our understanding of the same. In the second part, we review some empirical findings related to illiteracy in the context of literacy and we outline a perspective on the acquisition of reading and writing skills as well as other cognitive skills during (formal) education. Here we take the view that the educational system is a structured process for cultural transmission, and on this view, the educational system represents an institutionalized structure that subserves important aspects of socialization and cultural transmission.

STRUCTURAL AND FUNCTIONAL COMPLEXITY OF THE BRAIN

The human brain weighs approximately 1.3 kg and is divided into grey and white matter. The grey matter is formed into a convoluted surface of gyri and sulci and is densely packed with neurons, the information processing unit of the brain, with their local and more long-range neuronal connectivity (including short-distance inter-neurons and the dentritic trees and cell bodies, or somata, of long-distance inter-regional neurons). The white matter contains predominantly myelinated axons of the inter-regional neurons which constitute the regional and long-range cortico-cortical (e.g., inter-hemispheric tracts) as well as cortico-subcortical interconnectivity (e.g., sensory input and motor output tracts, Nieuwenhuys, Voogd, & van Huijzen, 1988). Besides the neocortex, grey matter is also found in the medial temporal lobe (including the hippocampus), the basal ganglia, the cerebellar cortex and nuclei, as well as various other subcortical nuclei in the midbrain and the brainstem (Nieuwenhuys et al., 1988). Microscopically, the brain is composed of about $\sim 10^{10} - 10^{12}$ neuronal processing units (i.e., neurons), each supporting $\sim 10^3 - 10^4$ axonal output connections and receiving, on average, the same number of dendritic and somatic input connections. The connectivity comprises in total some hundreds of trillions of interconnections and many thousand kilometers of cabling (Koch & Laurent, 1999; Shepherd, 1997).

The structural organization of brain connectivity resembles that of a tangled hierarchically structured and recurrently connected network (a "tangled hierarchy", cf., Hofstadter, 1999) composed of different functionally specialized brain regions. These regions consist of several types of processing elements (neurons) and synaptic connections (Felleman & Van Essen, 1991; Shepherd, 1997). The functional complexity of the nervous system arises from the non-linear, non-stationary (adaptive) characteristics of the processing units (i.e.,

neurons with synaptic parameters that can change across multiple time-scales of behavioral relevance), and the spatially non-homogeneous, parallel and interactive patterns of connectivity (**Figure 2**). This hardware architecture can in principle support a wide range of system dynamics (Maass, Natschläger, & Markram, 2004). The characteristics of the synaptic connections can change as a consequence of (information) processing and support various adaptive and learning mechanisms and thereby support seemingly self-organizing properties of cognition. From this perspective, learning and memory can be seen as a dynamic consequence of information processing and system plasticity (Petersson, Elfgren, & Ingvar, 1997; Petersson, Elfgren, & Ingvar, 1999) and recent work in cognitive neuroscience suggest that the organizational principles for cognitive functions depend on the patterns of distributed connectivity between functionally specialized brain regions as well as the functional segregation of interacting processing pathways - the dominant pattern of interconnectivity being recurrent (Arbib, 2003; Frackowiak et al., 2004; Ingvar & Petersson, 2000).
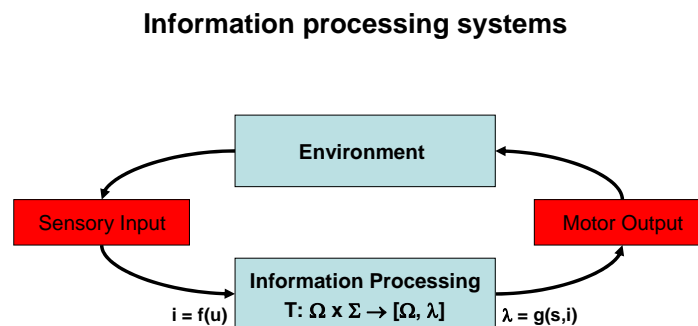

[Figure 2]

It has been suggested that an information processing system (Koch, 1999), physical or biophysical, which operate efficiently in the real word needs to obey several constraints: (1) it must operate at sufficiently high speeds; (2) it must have a sufficiently rich repertoire of computational primitives, with the ability to implement linear and non-linear, high-gain, operations; and (3) it must interface efficiently with the physical world via sensory input and motor output interfaces, matching various relevant time-scales. The neuronal membrane potential is the physical variable that can fulfill these requirements: for example, an action potential (the basis for neuronal signaling) changes the potential by ~100 mV within ~1 ms

and propagate ~1 cm or more within that time. Moreover, the membrane potential controls a large number of non-linear gates (i.e., ion channels) in each neuron (Koch, 1999). We will assume that important aspects of a neuronal state are well-characterized by its membrane potential (neuronal state variable). However, various adaptive phenomena imply that the membrane potential is not a complete description of the state of a given neuron at any given point in time (cf., adaptive parameters below). In any case, a complete state description of the neurons in a neural system provides us with a description of the state of the neural system as a function of time. We will return to this concept in an abstract form in the next section.

Since the network circuit hypothesis of McCulloch and Pitts (1943; see also Minsky, 1967) and the neuronal assembly theory of Donald O. Hebb (1949), several approaches to information processing in neural systems have suggested that information is represented as distributed neuronal activity and that information processing emerge from the interactions between different functionally specialized regions and neuronal groups (Arbib, 2003). In short, these approaches suggest that cognitive functions emerge from the global dynamics of interacting sub-networks (Petersson, 2005a).

INFORMATION PROCESSING MODELS

Information processing systems

[Figure 3]

Cognitive neuroscience approaches the human brain as a cognitive system: a system that functionally can be conceptualized in terms of information processing. Here and in the following subsections we will outline some aspects of the information processing concept; what is important here is how these concepts are interrelated and to a lesser extent their formal details. In general we consider a physical (or biophysical) system as an information

processing device when a subclass of its physical states can be viewed as cognitive/ representational and when transitions (T; cf., **Figure 3**) between these can be conceptualized as a process operating on these states by implementing well-defined operations on the representational structures. Information processing, (i.e., the state transitions) can thus be conceptualized as trajectories in a suitable state-space (cf., **Figure 3**).

We shall use the terms "representational" and "cognitive" interchangeably. It is important to note from the outset that when we are using "representational", this is not meant to implicitly entail a conceptualization of meaning in terms of a naïve "referential semantics". Rather, "representational" or "cognitive" is here referring to the functional role of a physical state with respect to the relevant processing machinery, and thus does not have an independent status separate from the information processing device as such (cf. e.g., Eck, 2000; Tanenbaum, 1990). Thus, the "internal semantics" of the system is only in complex and indirect ways related to the exterior of the system (e.g., via the sensorimotor interfaces, cf. e.g., Jackendoff, 2002) and there may be important aspects of processing which only has an internal significance (e.g., because of implementation constraints).
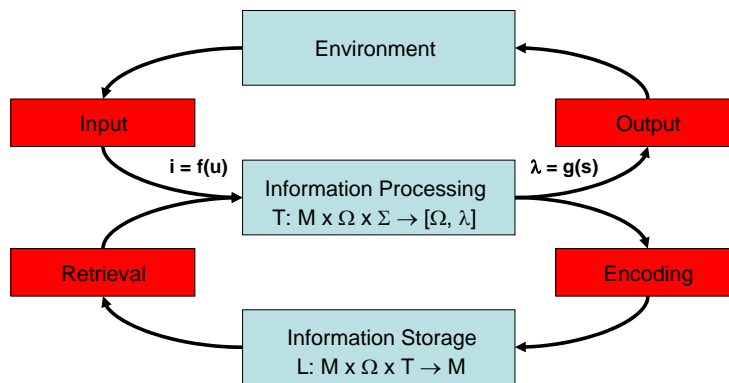
The framework of classical cognitive science and artificial intelligence assumes that information is coded by structured representations ("data structures") and that cognitive processing is accomplished by the execution of algorithmic operations ("rules"; ~T in **Figure 3**) on the basic representations ("primitive symbols") making up compositionally structured representations (Newell & Simon, 1976). This processing paradigm suggests that cognitive phenomena can be modeled within the framework of Church-Turing computability and effectively takes the view that isomorphic models of cognition can be found within this framework (cf. e.g., Cutland, 1980; Davis, Sigal, & Weyuker, 1994; Lewis & Papadimitriou, 1981). Language modeling in theoretical linguistics and psycholinguistics represents one example in which the classical framework has served (reasonably) well and all common formal language models can be described within the classical framework (cf. e.g., Partee, ter Meulen, & Wall, 1990).

A DEVELOPMENTAL PERSPECTIVE ON COGNITION

In order to incorporate development and learning in this picture, the processing dynamics, T, outlined in the previous section and in **Figure 3** has to be extended with an adaptive or developmental dynamics, L (**Figure 4**). For simplicity, let us focus on some particular cognitive module C, which is fundamental in the sense that all normal individuals develop cognitive capacities related to C; for example, let C be natural language. We can

conceptualize the development of the module as a trajectory in its model space M = [m | m can be instantiated by C] driven by the interaction with the environment in conjunction with innately specified developmental processes. In other words, at any point in time, t, one can imagine C being in a given state $m_C(t)$ [Note that "state" here refers to the model being instantiated by C rather than a cognitive state in the state-space of the processing system]. If we suppose that C incorporates an innately specified prior structure, we can capture this notion by a structured initial state of C, $m_C(t_0)$. Thus, as C develops, it traces out a trajectory in M determined by its adaptive dynamics L (**Figure 4**). If C and L are such that it (approximately) converges on a final model $m_C[F]$, this will characterize the end-state of the developmental process reached after time Δt_F, that is, $m_C(t_0+\Delta t_F) \approx m_C[F]$. We thus conceptualize development (as well as learning) in a cognitive system in terms of a forced system of coupled (i.e., interacting) dynamical systems (**Figure 4**).
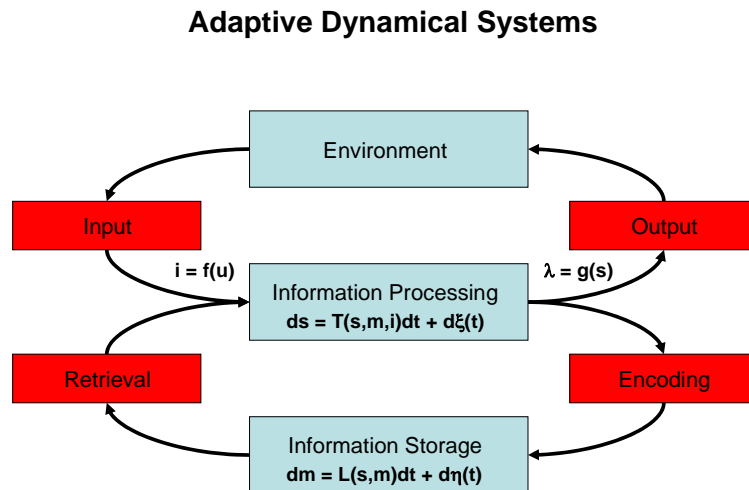
Adaptive Information Processing Systems

[Figure 4]

This outline is in its essentials similar to Chomsky's well-known hypothesis concerning language acquisition (e.g., Chomsky, 1980; Chomsky, 1986) where the module C is taken to be the faculty of language, L the language acquisition device, and the model space M the set of natural languages, which is determine by an innate universal grammar (see also Jackendoff, 2002). Different aspects of the universal grammar, including constraints and principles (Chomsky, 2000), are captured by M, L, and the initial state $m_C(t_0)$. Chomsky and others have argued extensively that the inherent properties of M, L, and $m_C(t_0)$ are determined by innately specified (genetic) factors, the genetically determined morphogenetic processes, in interaction with the physiochemical processes of cells. From this point of view, natural language acquisition is the result of an interaction between two sources of information: 1)

innate prior structure, which is likely to be language specific in nature as well as of general non-language specific type; and 2) the *environment*, both the linguistic and the extra-linguistic, which can be viewed as an interactive boundary condition for the developing system (Petersson, 2005a). The learning that characterizes language acquisition is largely implicit in nature (e.g., Forkstam, Hagoort, Fernandez, Ingvar, & Petersson, 2006; Forkstam & Petersson, 2005a; Forkstam & Petersson, 2005b; Petersson, Forkstam, & Ingvar, 2004).

Adaptive Dynamical Systems

[Figure 5]

In summary, the nervous system is naturally viewed as a (bio-)physical dynamic system and the temporal evolution of a given brain system, determined by its underlying neuronal dynamics, corresponds to transitions between physical states, which we here conceptualize as transitions between cognitive states or information processing. The brain's recurrent network architecture is a prerequisite for functional integration of functionally specialized brain regions (*functional modularity*). This serves as a basis for the dynamical systems perspective on cognitive function and suggests a form of functional modularity, which might be called *dynamic functional modularity*, which naturally lends itself to a description in terms of Marr's three (generalized) levels of analysis: the cognitive-, the dynamical system-, and the implementation level. We thus arrive at a dynamic conceptualization of a cognitive learning system C in terms of: (1) a *functional architecture* specifying its structural organization (e.g., network architecture); (2) a *representational dynamics* specifying its information processing dynamics (e.g., the evolution of membrane potentials and the generation of action potentials); and (3) a *learning dynamics*, which specifies its adaptive parameters (for information storage in a general sense; e.g., synaptic

parameters) and the dynamical principles governing the time evolution of the adaptive parameters (e.g., co-occurrence or covariance based Hebbian learning, cf., Arbib, 2003; Gerstner & Kistler, 2002; Koch, 1999).

In short, a developmental learning system can be conceptualized as coupled dynamical systems, one for processing of information in interaction with another dynamical sub-system for learning, memory, and development (cf., **Figure 5**). However, general dynamical system theory (Lasota & Mackey, 1994; Ott, 1993) is in a sense obviously too rich as a framework for formulating explicit models of cognitive brain functions (Petersson, 2005a); what is crucially needed is a specification of cognitively relevant constraints and processing principles as well as constraints and processing principles relevant for the neurobiological networks subserving information processing in the brain. Thus, in a very important sense, most of the empirical and theoretical work necessary for a deeper understanding of cognitive functions remains to be pursued in order to specify detailed and integrated models of cognition, development, and learning.

The point of the discussion, so far, has been to specify explicitly the form such models can take and how the concepts behind them are interrelated, serving as a foundation in the future quest for a more profound understanding of developing cognitive systems, most prominently represented by the human brain and its capacity to acquire a natural language. What is important here is to understand how these concepts are interrelated and how they serve as a context and a background to the second part of this chapter. In the second part, we will start by briefly discuss how cognitive states, viewed as physical states, and operations on these states (i.e., information processing) can be empirically characterized with functional neuroimaging techniques as well as behaviorally, and in the final part we will give an overview of some recent empirical results related to literacy/illiteracy.

LANGUAGE AND LITERACY

Since Paul Broca (1861, Broca's region ~ Brodmann's areas (BA) 6/44/45/47) and Carl Wernicke (1874, Wernicke's region ~ posterior BA 22 and inferior BA 39/40) identified separate brain regions specialized for different aspects of language processing, it is well-accepted that the human brain instantiates a distributed network supporting natural language processing. From a cognitive neuroscience perspective, natural language is a brain system of knowledge, a generative system for communicative use (Baggio, Van Lambalgen, & Hagoort, 2007, in press; Chomsky, 1986). During language comprehension, incoming sounds or orthographic patterns trigger memory retrieval processes that make available phonologic,

syntactic, and semantic features of words and these structures are integrated (unified) at the sentence and discourse levels, typically resulting in a coherent interpretation of the input. Similar processes are at work in language production, resulting in compositionally structured serialized (linearized) sounds or orthographic patterns in the service of communication. Memory retrieval and structure integration (unification) play an important role in both comprehension and production (Forkstam & Petersson, 2005a; Hagoort, 2005; Jackendoff, 2002; Shieber, 1986; Vosse & Kempen, 2000).

The neural structures involved in retrieval of stored language knowledge are likely to have evolved from, and show an overlap with, structures involved in retrieving general knowledge and working memory (Baddeley, 1996, 2000; Baddeley, Gathercole, & Papagno, 1998; Jackendoff, 2002), including prefrontal, temporal, and inferior parietal regions. In addition to the medial temporal lobe memory system, which plays a central role in declarative memory operations (Bastiaansen & Hagoort, 2006; Miller, Li, & Desimone, 1991; Petersson, Gisselgård, Gretzer, Baddeley, & Ingvar, 2006), a large number of brain regions have been linked to the retrieval of information from long-term memory and its utilization in working memory, including prefrontal, temporal, parietal, anterior cingulate, and cerebellar regions. Among the cortical regions that have been specifically associated with retrieval of lexical information in the context of language comprehension are the central and posterior parts of the left middle and superior temporal gyri, and the posterior inferior frontal gyrus (cf. e.g., Indefrey & Cutler, 2005). Unification operations related to the domains of phonology, syntax, and semantics are thought to be carried out in a set of brain regions including the left inferior frontal gyrus (Broca's region and surrounding tissue: BA 6/44/45/47), and possibly the left posterior superior temporal/inferior parietal region (BA 22/39/40). There appears to be a degree of regional specificity for phonology, syntax, and semantics in the left inferior frontal gyrus, (Bookheimer, 2002; Hagoort, Hald, Baastiansen, & Petersson, 2004; Petersson et al., 2004). The language network, characterized with PET and FMRI, is thus becoming increasingly well understood. However, the resulting picture is static, emphasizing mainly the structural aspects of the language network and does not capture the dynamic properties of the language processing device (Bastiaansen & Hagoort, 2006). Thus, the information obtained with PET and FMRI needs to be complemented with information derived from EEG and MEG, which record neuronal activity on a millisecond time scale (Bastiaansen & Hagoort, 2006). Bastiaansen and Hagoort (2006) provide a review of the rapid, oscillatory changes during language processing and give reasons for why these oscillatory changes provide a window on the neuronal dynamics of the language system. They argue that it has become

increasingly clear on the basis of functional neuroimaging studies that the view that there is a one-to-one mapping between a brain area and a specific component of a cognitive function is far too simplistic and suggest that individual cortical areas can be recruited dynamically in more than one functional network (Mesulam, 1998). They suggest that the dynamic recruitment of participating cortical and subcortical regions is reflected in the patterns of synchronization and desynchronization of neuronal activity. The idea is that synchronous, repetitive neuronal firing of action potentials facilitates the activation of functional networks because it increases the probability that neurons entrain one another in synchronous firing and that synchronization/desynchronization play a crucial role in the dynamic linking of regions that are part of a given functional network (cf. e.g., Fries, 2005). However, this domain of functional neuroimaging is in its infancy and many issues remain unknown or unexplored. Here it is important to note, in relation to the first part of this chapter, which provided a somewhat abstract conceptualization of cognitive systems as coupled dynamical systems on appropriate state-spaces (cf., **Figure 5**), that the various functional neuroimaging methods (PET/FMRI/EEG/MEG) provide techniques for direct or indirect quantitative measurements of aspects of the physical states of the brain, which are the concrete instantiations of the cognitive states previously referred to. Although most of the empirical and theoretical work necessary for a deeper understanding of cognitive functions remains to be developed, the current functional neuroimaging techniques provide powerful and useful tools in this quest for a more detailed and integrated model of cognition.

Aspects of language can also be an object of meta-linguistic awareness: explicit processing and the intentional control over aspects of phonology, syntax, semantics, discourse, as well as pragmatics. Children gradually create explicit representations and acquire processing mechanisms that allow for reflecting and analyzing different aspects of language function and language use (Karmiloff-Smith, Grant, Sims, Jones, & Cuckle, 1996). Children do not learn language passively but actively construct representations on the basis of linguistically relevant constraints and abstractions of the linguistic input (Karmiloff-Smith et al., 1996). When children subsequently learn to read, this has repercussions on the phonological representations of spoken language (Morais, 1993; Petersson, Reis, Askelöf, Castro-Caldas, & Ingvar, 2000; Ziegler & Goswami, 2005). During the acquisition of reading and writing skills, the child creates the ability to represent aspects of the phonological component of language by an orthographic representation and relate this to a visuographic input-output code. This is commonly achieved by means of a supervised learning process

(i.e., teaching), in contrast to natural language acquisition, which is largely a spontaneous, non-supervised, and self-organized acquisition process.

Reading and writing are cognitive abilities that depend on human cultural evolution (Vygotsky, 1962). Writing is a relatively late invention in human history (some 5000-6000 years ago) and it seems unlikely that specific brain structures have developed for the purpose of mediating reading and writing per se. Instead, it is likely that reading and writing skills are supported by pre-adapted brain structures. A pre-adaptation is a structure that has evolved in an ancestral population to serve a specific adaptive function but has come to serve as a new means for a different end in a descendant population. Pre-adapted structures possess, by definition, a prior functionality and some of these might carry characteristics that make them suitable substrates for supporting new human cultural tools; the idea here being that they require relatively limited changes to adapt them to their new domain by taking advantage of prior evolved functional capacity. This suggests that such structures may not acquire an arbitrary new functional capacity (although, this is not logically ruled out either, given the limited primitive functional capacity necessary for universal computation, cf. e.g., Davis et al., 1994; Minsky, 1967; Wells, 2005). With respect to literacy, it has been argued that the architecture of the human brain is limited and shares many traits with other non-human primates (Dehaene, 2004). Dehaene (2004) suggests that the human brain is laid down under tight genetic constraints, yet with a fringe of adaptive capacity, and he argues that cultural acquisitions are only possible to the extent that these can be accommodated within the range of neural plasticity, by adapting ("customizing"/"configuring") pre-existing neural predispositions. Dehaene (2004) also suggests that the efficiency of education should be greatly enhanced by using teaching strategies that capitalize upon the pre-existing representations that young children possess prior to entering school (cf., Ardila, 2004).

In what ways do cognitive and neural processes interact during development, and what are the consequences of this interaction for theories of learning? Quartz and Sejnowski (1997) attempted to sketch a neural framework addressing these issues, so-called neural constructivism, suggesting that there is an active constructive interaction between the developing system and the environment in which it is embedded. Development, learning, and cognitive skill acquisition implies that the neural infrastructure changes its processing characteristics as a result of these processes. Given the co-localization of memory (i.e., here in the general sense of adaptive changes) and processing in the brain (Petersson et al., 1997; Petersson, Elfgren et al., 1999), this entails a system with properties that are time-dependent ("non-stationary") and the effected changes in the processing characteristics are driven by and

result from the outcome of an interaction between neurobiological maturation and experiential learning processes. Post-natal human cerebral development is a progressive process that lasts at least until early adulthood. This suggests the possibility of a complex interaction between environmentally derived information and prior genetic structure, which takes place during ontogenetic development, in constructing mental representations and shaping processing networks (Thompson et al., 2001; Thompson et al., 2000).

Human natural language, a major vehicle for cultural transmission, serves as a good illustration of the issues involved (cf., Hauser, Chomsky, & Fitch, 2002; Nowak, Komarova, & Niyogi, 2002). In order to effectively solve real world learning problems it is typically necessary to incorporate relevant prior structure (i.e., prior knowledge in the form of a structured initial state and prior properties of adaptive acquisition devices; cf., **Figure 5** and associated text in the first part of this chapter) in the functional architecture. This is a general and well-accepted insight from work in formal learning theory (e.g., Jain, Osherson, Royer, & Sharma, 1999) as well as in statistical learning theory (e.g., Cherkassky & Mulier, 1998; Geman, Bienenstock, & Doursat, 1992; Haykin, 1998; Vapnik, 1998). The extent to which prior information is invoked in an explanatory scheme has the effect of shifting the explanatory burden from ontogenetic development and learning to phylogenetic adaptation, which of course requires its own explanation. On the other hand, prior innate structure can significantly reduce the complexity of the acquisition problem by constraining the available model space M (for a given cognitive component), thus alleviating the extent of the search problem that the child is confronted with in order to converge on an appropriate final model $m_C[F]$. Chomsky's hypothesis of the existence of a universal competence grammar, determined by the language acquisition device and the initial state of the individual's language faculty is an example of this (Chomsky, 1965, 1986).

It has been suggested that natural language arises from three distinct but interacting adaptive systems: individual learning, cultural transmission, and biological evolution (Christiansen & Kirby, 2003). The adaptive character of evolution as well as individual learning ("adaptation of the individual's knowledge") is undisputed but this is less clear for cultural development. Christiansen and Kirby (2003) argue that the knowledge of particular languages persists over time by being repeatedly used to generate language output and this output represents input to the language acquisition device of the individual learner of the next generation. It is likely that aspects of natural languages have adapted to the constraints set by the language acquisition device of individual learners. Constraints on language transmission are thus set by prior structures related to the language acquisition device determined by the

outcome of biological evolution. However, Christiansen and Kirby (2003) suggest that if there are features of language that must be acquired by all learners, and there are constraints or selection pressures on the reliable and rapid acquisition of those features, then an individual who is born with such acquisition properties will have an advantage, exemplifying the so-called Baldwin effect of genetic assimilation, whereby acquired features can become innate. These suggestions are consistent with Chomsky's perspective that the universal competence grammar is determined by the language acquisition device and the initial state of the individual.

Literacy, reading and writing, as well as printed media represent extensive cultural complexes and, like all cultural expressions, they originate in human cognition and social interaction. Goody's work on literacy emphasizes the role that written communication has played in the emergence, development, and organization of social and cultural institutions in contemporary societies (e.g., Goody, 2000). The emergence of writing transformed human culture, including the ability to preserve speech and knowledge in printed media. This allowed societies with a literate tradition to develop and accumulate knowledge as well as control over their environment and living conditions. In addition, the nature of oral communication has a considerable effect upon both the content and transmission of the cultural repertoire of a society. For example, the content of the cultural traditions and knowledge has to be held in memory when a written record is not an option. Instead, individual memory will mediate the cultural heritage between generations and new experience will be integrated with the old by a process of interpretation. The invention of new communication media have significant impact on the way information is created, stored, retrieved, transmitted, and used as well as on the cultural evolution as a whole. Furthermore, reading and writing makes possible an increasingly articulate feedback as well as independent self-reflection and promotes the development of meta-cognitive skills; while auditory-verbal language use is oriented towards content, aspects of this knowledge can become explicitly available to the language user in terms of cognitive control and analytic awareness. It has thus been suggested that the acquisition of reading and writing skills, as well as formal education more generally, facilitates this through a process of representational construction and reorganization (Karmiloff-Smith, 1992).

We will leave the general discussion at this point and move on to experimental results related to literacy and education as seen from the point of view of cognitive neuroscience, that is, we will focus on empirical studies investigating the left-side interaction of **Figure 1**, that between the individual and his or her environment with its sources for cultural

transmission. In particular, we will review some recent cognitive, neuroanatomic, and functional neuroimaging data that, taken together, suggest that formal education influence important aspects of the human brain and provide strong support for the hypothesis that the functional architecture of the brain is modulated by literacy. In particular, we will focus on results from a series of experiments with an illiterate population and their matched literate controls living in the south of Portugal.

LITERACY FROM A COGNITIVE NEUROSCIECE POINT OF VIEW

Education plays an essential role in contemporary society. Acquiring reading and writing skills as well as other cognitive skills during formal education can be viewed as a structured process of cultural transmission. These institutionalized structures subserve important aspects of socialization and cultural transmission. The study of illiterate subjects and their matched literate controls provides an opportunity to investigate the interaction between neurobiological and cultural factors on the outcome of cognitive development and learning (cf., **Figure 1**). The careful study of illiteracy can contribute to an understanding of the organization of human cognition without the confounding factor of education, and from a practical point of view, investigations of illiteracy can contribute to disentangle the influence of educational background on cognitive test performance in clinical neuropsychological practice; it is well-known that educational variables significantly influence performance on many neuropsychological tests (Lezak, Howieson, & Loring, 2004; Petersson & Reis, 2006; Reis & Petersson, 2003; Silva, Petersson, Faísca, Ingvar, & Reis, 2004) and it is important to distinguish, for example, the effects of brain damage from the influence of individual educational history. This is particularly important since reading and writing skills are still far from universal at the beginning of the 21st century. At present, it is estimated that there are close to one billion illiterate humans in the world (about two thirds are women; UNESCO, 2003), whereas the mean educational level is only about 3-4 years of schooling (Abadzi, 2003).

THE STUDY POPULATION OF SOUTHERN PORTUGAL

The fishermen village Olhão in southern Portugal, where all of our studies on illiteracy have been conducted, is socio-culturally homogeneous and the majority of the population has lived most of their lives within the community. Mobility within the region has been limited and the main source of income is related to agriculture or fishing. Illiteracy occurs in Portugal because of the fact that forty or fifty years ago it was common for the older daughters of a

family to be engaged in daily household activities at home and therefore did not enter school. Later in life they may have started to work outside the family. In larger families, the younger children were generally sent to school when they reached the age of 6 or 7 while the older siblings typically helped out with the younger siblings at home. Thus, the illiterate subjects we have investigated are illiterate for reasonably well-defined socio-cultural reasons and not due to individual causes (e.g., learning difficulties or early central nervous system pathologies).

Literate and illiterate subjects live intermixed in this region of Portugal and participate actively in this community on similar terms. Illiteracy is not perceived as a functional handicap and the same socio-cultural environment influences both literate and illiterate subjects to a similar degree. Some of the literate and illiterate subjects in our studies are from the same family, increasing the homogeneity in background variables. In addition, most of the literate subjects participating in our studies are not highly educated and typically they have had only ~4 years of schooling. In the present context, it is important to ensure that the subjects investigated are not cognitively impaired and also that the illiterate are matched to the literate subjects in as many relevant respects as is possible, except of course for the consequences of not having had the opportunity to receive a formal education. In our studies we have attempted to match the different literacy groups in terms of several relevant variables, including for example age, gender, socio-cultural background, and level of everyday functionality (for a more detailed characterization of our study population and our selection procedures see Reis, Guerreiro, & Petersson, 2003). These protocols and procedures ensure with reasonable confidence that the illiterate subjects are cognitively normal, that their lack of formal education results from specific socio-cultural reasons and because of low intelligence, learning disability, or other pathology potentially affecting the brain. The illiterate subjects and their literate controls included in our studies are comparable along socio-economic dimensions as well.

FUNCTIONAL AND NEUROANATOMICAL DIFFERENCES BETWEEN LITERACY GROUPS

In an early PET study of literate and illiterate subjects, we compared the two literacy groups on an immediate verbal repetition task. The subjects were instructed to repeat words or pseudowords, one item presented at a time recorded from a native speaker (Petersson et al., 2000). We chose to investigate the word/pseudoword repetition task because it is known to be a test of phonological processing/awareness and correlates with reading acquisition (cf.,

below). In our view this task is more ecologically relevant than many other tasks which also taxes phonological processing and phonological awareness (e.g., initial phoneme deletion, phoneme counting, phone similarity classification etc.; cf., below). Within-group comparisons showed a more prominent left-sided inferior parietal (BA 40) activation in word- versus pseudoword repetition in the literate group, while in the reverse comparison (pseudowords versus words) the literate group displayed significant activations in the anterior insular cortex (BA 14/15) bilaterally and in the right inferior frontal/frontal opercular cortices (BA 44/45/47), left perigenual anterior cingulate cortex (BA 24/32), left basal ganglia, and the midline cerebellum. In the illiterate group, a single significant activation was observed in the right middle frontal/frontopolar region (BA 10). Direct group comparisons largely confirmed these differences. In particular, the significantly greater activation of the left inferior parietal region (BA 40) in the literate compared to the illiterate group was related to a greater activation of this region in the word versus pseudoword comparison.

A central cognitive capacity related to spoken language is verbal working memory which supports several higher cognitive functions, including language and reasoning (Baddeley, 1986, 2003). According to the Baddeley-Hitch model of working memory is composed of a central executive with two support systems, the phonological loop for storing verbal information, and the visual sketch pad for storing visuospatial information. The phonological loop consists of the phonological store and an articulatory rehearsal process. The functional-anatomical correlate of the phonological store is putatively the left inferior parietal region (BA 39/40) together with parts of the superior temporal cortex (BA 22, Becker, MacAndrew, & Fiez, 1999), while the articulatory rehearsal process is related to a left frontal circuit including Broca's region (BA 44) and parts of the left premotor cortex (BA 6, Smith & Jonides, 1998, 1999). Taken together with the behavioral findings outlined below, PET results suggest that the functional architecture of auditory-spoken language is influenced by literacy and that the acquisition of reading and writing skills modify aspects of phonological processing.

A complementary approach to the analysis of functional neuroimaging data outlined in the previous paragraph, which investigates differences between conditions and experimental groups in terms of functionally specialized regions, takes a network perspective on cognitive brain function in order to explore functional integration in terms of functional connectivity (see e.g., Friston, 1994; Ingvar & Petersson, 2000; Petersson et al., 2006). As already outlined in the first part of this chapter, information is thought to be represented as distributed activity patterns, while information processing subserving cognitive functions is

thought to emerge from the interactions within and between different functionally specialized regions. Structural equation modeling provides one approach to characterize network interactions and to test network hypotheses explicitly by investigating the covariance structure observed between a set of brain regions. Petersson et al. (2000) employed a structural modeling analysis of the PET data described above in order to characterize the pattern of interactions between brain regions during immediate verbal repetition in literate and illiterate subjects (for limitations see Petersson, Nichols, Poline, & Holmes, 1999a, 1999b). The network analysis aimed at characterizing the functional organization in terms of effective connections between regions in a functional-anatomical model. Our objective was to construct a simple network model that could explain a sufficient part of the observed covariance structure in both groups during both word and pseudoword repetition. At the same time we required that the network model should be both theoretically and empirically plausible based on the available literature on the functional organization of language (for details see Petersson et al., 2000).

In terms of the network interactions, the results showed no significant difference in the literate group when they repeated words or pseudowords. This suggests that the interactions observed in the functional network support both word- or pseudoword repetition in a similar way. There was neither any significant difference between the literate and illiterate group in the word repetition condition. In contrast, there were significant differences between word and pseudoword repetition in the illiterate group and between the illiterate and literate group in the pseudword condition. The differences between groups were mainly related to the phonological loop, in particular, the interaction between Broca's region and the inferior parietal region.

The absence of a significant difference between word and pseudoword repetition in the literate group relates to the fact that the network interactions were similar in both conditions, which suggests that the literate subjects automatically recruit the same processing network during immediate verbal repetition irrespective of whether they repeat words or pseudowords. In contrast, this was not the case for the illiterate group. Although the functional network investigated was the same as that in the literate group, the interaction pattern between brain regions were different from that observed in the literate group, consistent with the suggestion that phonological processing is differently organized in illiterate individuals when confronting novel, but phonotactically legitimate, phonological patterns. We suggest that the observed differences are due to the different developmental background between the two groups related to the acquisition of reading and writing skills.
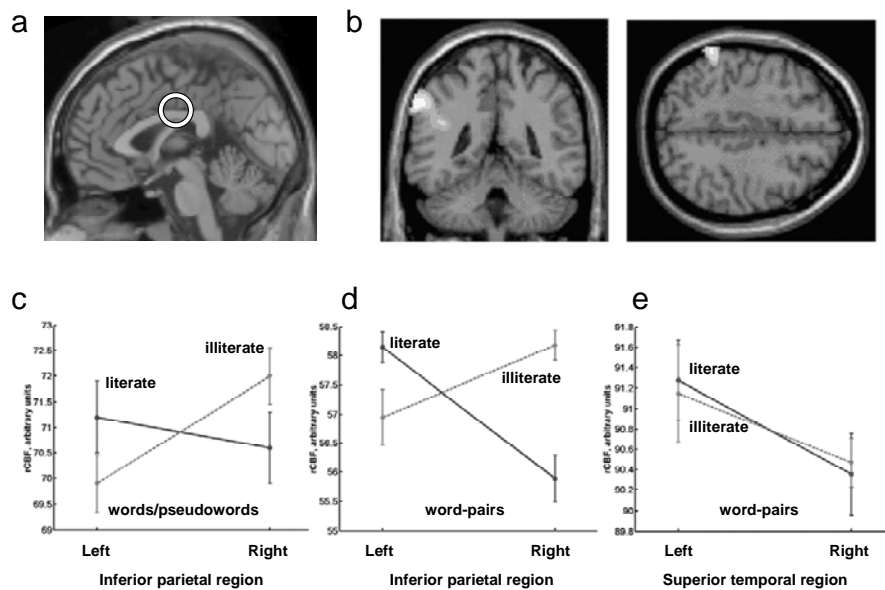
The observed differences in interaction patterns related to the phonological loop between literate and illiterate subjects are in line with the suggestion that the parallel interactive processing characteristics of the language system, in particular with respect to phonology, differ between literate and illiterate subjects (Petersson et al., 2000). Given what is known about pre-literate phonological development (Goswami & Bryant, 1990; Jusczyk, 1997; Ziegler & Goswami, 2005) and for theoretical reasons as well as (Olson, 1996), and in line with our previous interpretation of our behavioral results, the difference in phonological processing between literate and illiterate subjects is likely related to aspects of sub-syllabic phonological structure.

HEMISPHERIC DIFFERENCES

Early accounts, based on patient descriptions, suggested that illiterates were less prone to develop persistent aphasia following localized cerebral lesions. Later more systematic studies have negated this (Castro-Caldas, Reis, & Guerreiro, 1997). Still, one may wonder whether there are also neuroanatomic correlates corresponding to literacy status, that is, whether a specific form of cultural transmission makes a systematic influence on a ontogenetic level detectable in terms of differences in the functional organization as well as brain morphology.

It is well-known that the corpus callosum, the large fiber bundle that interconnects the left and the right brain hemisphere, develops during childhood and young adulthood. In particular, there is an active myelination process of the neuronal axons running through this structure in order to establish efficient communication between the two hemispheres (Giedd et al., 1996). Recent evidence suggest that the posterior mid-body part of the corpus callosum undergoes extensive myelination during the years of reading acquisition, that is, from 6 to 10 years of age (Thompson et al., 2000). The fibers that cross over in this region of the corpus callosum interconnect the left and right parieto-temporal regions (for a general review see e.g., Zaidel & Iacoboni, 2003). The parieto-temporal regions of the brain, in particular in the left hemisphere is related to language processing, verbal working memory, and reading, and it has been suggested that the corpus callosum plays an important role in the inter-hemispheric exchange of orthographic and phonological information during reading. A study of the morphology of the corpus callosum in literate and illiterate subjects suggested that the posterior mid-body region (**Figure 6a**) is thinner in the illiterate compared to the literate subjects (Castro-Caldas et al., 1999). Petersson et al. (1998) suggested that this may be related to a difference in the inter-hemispheric interactions between the left and right parieto-temporal cortices in the two literacy groups. Behavioral and lesion data have suggested,

though not unambiguously so, that certain aspects of language processing in illiterate individuals recruit bilateral brain regions to a greater extent than literate subjects (for a review see e.g., Coppens, Parente, & Lecours, 1998). In a recent study (Petersson, Reis, Castro-Caldas, & Ingvar, in preparation), we attempted to characterize the hemispheric left-right differences in two independent datasets acquired with PET from two different samples of illiterate subjects and their matched literate controls. In the first dataset, in which the subjects repeated words and pseudowords, we explored the possibility of a left-right difference between literacy groups, predicting a greater left-right difference in the literate compared to the illiterate subjects in the inferior parietal region. In order to test this prediction we investigated regions of interest in the angular-supramarginal region (BA 39/40). In a random effect analysis, the left-right difference was greater in the literate group compared to the illiterate for both word and pseudoword repetition (**Figure 6c**). In the second sample, in which subjects listen to and encoded word-pairs, we attempted to replicate this finding.

[Figure 6]

Again, the literate group showed greater left-right difference in the angular-supramarginal region (BA39/40) compared to the illiterate subjects (**Figure 6b and d**). In order to test the specificity of our results with respect to the left - right differences in the inferior parietal cortex, we followed up on a suggestion that infants are left lateralized in the superior

temporal gyrus when listening to speech or speech-like sounds (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002), and also investigated the superior temporal region (BA 22/41/42). The results showed that both literacy groups were similarly left lateralized in this region (**Figure 6e**) suggesting that the functional lateralization of early speech related brain regions do not depend on literacy. Consistent with these findings, Ostrosky-Solis and colleagues (2004), recording cortical evoked potentials (ERPs) during a verbal memory task in literate and illiterate subjects, observed hemispheric differences between groups in the parieto-temporal regions, while suggesting that the left hemisphere predominantly mediates language processing in both literacy groups.

It is well accepted that both hemispheres play a role in language processing. However, the results outlined here lend support to the suggestion literacy influences the functional hemispheric balance in inferior parietal language related regions. One may speculate that acquiring reading and writing skills at the appropriate age shapes not only the local morphology of the corpus callosum but also the degree of functional specialization as well as the pattern of interaction between the interconnected parieto-temporal regions. Thus there might be a causal connection between reading and writing acquisition, the development of the corpus callosum, and the hemispheric differences reported here (Petersson & Reis, 2006).

In recent work with voxel-based morphometry, we have investigated a group of 22 illiterate and 26 matched literate controls in order to characterize the impact of reading and writing skills on brain morphometry (Reis, Silva et al., 2006). Preliminary findings suggest relatively subtle grey matter density differences between literacy groups, mainly located in the left occipital cortex (BA 18/19; literate > illiterate), while the white matter density differences were much more prominent and related to the occipito-temporal- ("what") pathway (in the vicinity of right BA 18/19/20 and left BA 20/37; literate > illiterate). These results suggest that the density of neuronal connectivity is relatively more affected by literacy and education compared to neuronal density as such. Similar morphometric findings in dyslexic subjects have been reported, suggesting reduced grey- and white matter densities in different brain regions known to be engage in reading tasks (Brambati et al., 2004; Brown et al., 2001; Silani et al., 2005). In short, the results suggest white matter differences related to brain regions that are dedicated to the visual information processing, suggesting that learning how to read and write modifies the density of white matter adjacent to brain regions involved in the processing of written language. The fact that the differences between literacy groups were mainly located to the white matter suggests that the acquisition and maintenance of

reading and writing skills promote the communication in a functionally dedicated neocortical network.

COGNITIVE DIFFERENCES BETWEEN LITERACY GROUPS

Behavioral studies have demonstrated that literacy/illiteracy as well as the extent of formal education influence the performance of several behavioral tasks commonly used in neuropsychological assessment (for recent reviews see Petersson & Reis, 2006; Petersson, Reis, & Ingvar, 2001). For example, it appears that the acquisition of written language skills modulates aspects of spoken language processing (e.g., Mendonça et al., 2002; Silva et al., 2002). Additional results suggest that formal education influences some visuospatial skills (e.g., Reis, Petersson, Castro-Caldas, & Ingvar, 2001). However, it is still unclear which cognitive processes and brain mechanisms mediate these effects of literacy and education. A detailed understanding of which parts of the cognitive system and which processing levels are affected is still lacking. The basic idea is that literacy influences some aspects of spoken language processing related to phonological processing, in particular the processing of sub-syllabic structure, verbal short-term working memory as well as visuomotor skills related to reading and writing.

COLOR MAKES A DIFFERENCE - OBJECT NAMING

Several studies have indicated that the level of formal education and/or literacy influence the performance when subjects name two-dimensional (2D) pictorial representations of objects (e.g., Reis, Guerreiro, & Castro-Caldas, 1994). Naming objects or their 2D pictorial representations are common every day tasks and the performance on simple object-naming tasks is dependent on the systems for visual recognition, lexical retrieval, and the organization of speech output as well as the interaction between these systems (Levelt, 1989). In our study population, practice in interpreting schematic 2D representations commonly took place simultaneously with the acquisition of written Portuguese and other symbolic representations during school attendance. Moreover, reading and writing depend on advanced visual and visuomotor skills in coding, decoding, and generating 2D representations. It is thus likely that the interpretation and production of 2D representations of real objects as well as the coding and decoding of 2D material in terms of figurative/symbolic semantic content is more practiced in literate compared to illiterate individuals, who generally have received little

systematic practice in interpreting conventional visuo-symbolic representations. We thus speculated that there may be differences in 3D and 2D object-naming skills between literate and illiterate individuals. In a simple visual naming experiment in which the participants named common everyday objects, Reis, Petersson et al. (2001) reported differences between literate and illiterate subjects related to 2D object naming but found no difference when subjects named real 3D objects, both with respect to naming performance and in terms of response times. In addition, the two groups dissociated in terms of their error patterns, with the illiterate group is more prone to make visually related errors (recognition failure or visual recognition error, e.g., pen instead of needle), whereas the literate group tended to make semantically related errors (no lexical access or lexical semantic errors, e.g., necklace instead of bracelet). Although the results with 2D line drawings and real objects were clear in the study of Reis, Petersson et al. (2001), the results with colored photos did not clearly dissociate between the literacy groups in terms of 2D vs. 3D naming skills. We therefore speculated that the semantic significance of object color might play a role, in particular for the illiterate subjects because they are prone to be driven by semantic rather than formal aspects of stimuli or information. In a recent follow-up study (Reis, Faísca, Ingvar, & Petersson, 2006), we presented common everyday objects as black and white (i.e., grey scaled) as well as colored drawings and photos in an immediate 2D object naming task. Consistent with the results already outlined, the literate group performed significantly better than the illiterate group on black and white items (i.e., both line drawings and photos). In contrast, there was no significant difference between literacy groups on the colored items. Interestingly, the illiterate participants performed significantly better on colored line drawings compared to black and white photos. Further investigations also suggest that the color effect is related to the semantic value of the color in the sense that the effect seems more pronounced for objects with no or little consistency in the color-object relation compared to objects with a consistent relation to its color (e.g., lemons are yellow). Taken together these results are consistent with the hypothesis that orthographic knowledge is an integral component of the general visual processing system (Patterson & Lambon Ralph, 1999), suggesting that the acquisition of alphabetic orthographic knowledge affect specific components of visual processing.

THE IMPACT OF LITERACY ON VISUOMOTOR INTEGRATION

The impact of literacy and formal education on non-verbal cognitive domains has not been fully explored. In an earlier study, Ostrosky-Solis, Efron and Yund (1991) made an

interesting observation about the visual scanning behavior in non-literate subjects. The nature of these differences suggests that the acquisition of reading skills might cause literate subjects to adopt more consistent scanning paths. In more recent work, Matute and colleagues (2000) demonstrated that literacy also plays a significant role on visuo-constructional tasks. These result lend support to the idea that the reading level might be related to the mechanisms responsible for variation in performance on visuo-perceptual tests (Byrd, Jacobs, Hilton, Stern, & Manly, 2005) and is consistent with previous findings (Le Carret et al., 2003) which showed that individuals with a lower educational level have less effective visual search strategies and produce fewer successful responses to target items appearing in the lower half of 2 x 2 response matrices. Although the results of these studies suggest poor strategic search skills in illiterate, low-literate subjects and poor readers, it is possible that the low performance is related to poor shape recognition skills (cf., the previous object naming sub-section).

Another line of evidence concerning the effect of reading on visual scanning mechanisms comes from studies performed in literate populations that have acquired orthographies with different reading directions (left-to-right and right-to-left) suggesting that the reading system bias the visual scanning behavior in certain circumstances. One of the first studies that reported an influence of reading habits on visual recognition of English words (read from left to right) and Yiddish words (read from right to left) presented in the left and right visual fields to subjects who could read both languages (Mishking & Forgays, 1952). More recently, Chokron and Imbert (1993) used a line-bisection task to investigate the impact of reading and writing habits on visuomotor integration skills. The authors analyzed the performance of French and Israelis subjects and the bisection performance was found to depend on the reading habits of the subjects.

In a recent study, Bramão and colleagues (2007, in press) demonstrated that the acquisition of literacy also modulates non-verbal cognitive domains when testing illiterate and literate subjects on a visuomotor integration task with non-linguistic stimuli. The results showed that the literate subjects were significantly faster in detecting and touching targets on the left compared with the right side of the screen. In contrast, the presentation side did not affect the performance of the illiterate group. It is clear that the act of reading and writing in an alphabetic language engages cognitive processes related to both the systematic scanning of space as well as motor integration. Consistent with this idea, our results suggest that visual scanning, detection, and pointing at non-linguistic targets are modulated by the acquisition of reading and writing skills and represent new evidence that a preferred left-to-right reading

direction influences visual scanning behavior. Reading and writing skills depends on both right hemisphere- (e.g., visuospatia strategies) and the left hemisphere functions (e.g., language and writing), which is likely to promote an increased asymmetry in information transfer between the hemispheres. This suggestion is consistent with both the left – right differences and differences in the structure of the corpus callosum previously outlined in the two literacy groups.

ECOLOGICAL RELEVANCE

Formal education is not only associated with literacy but also with the acquisition of a broader knowledge-base of general information as well as strategies to process this information in a more elaborate, systematic, and abstract manner. Thus, education catalyzes the development of several cognitive skills in addition to reading and writing. Task selection is thus of importance when investigating populations with different cultural backgrounds. In particular when the objective is to interpret differences in performance in cognitive terms and it is important in this context that the task is of comparable ecological relevance to the populations investigated (Petersson et al., 2001). This goes beyond matching populations for background variables related to socio-economic status, etc. (cf. e.g., Coppens et al., 1998; Reis & Petersson, 2003). This is illustrated by the results from a study of semantic fluency by Silva et al. (2004).

Verbal fluency tasks (i.e., production tasks in which subjects generate as many words as possible according to some given criterion during a limited amount of time) are commonly used in neuropsychological assessment because they are easy to administer, sensitive to brain damage and cognitive deterioration, and have been applied to groups of different cultural backgrounds. Clear and consistent differences between literacy groups have been reported when a phonological fluency criterion is used. In contrast, several studies using semantic criteria have yielded inconsistent results (Silva et al., 2004). Reis et al. (2003) suggested that the non-convergence of results could be related to the ecological or cultural relevance of the chosen semantic criterion. In order to investigate this issue in greater detail, Reis et al. (2001; 2003) decided to use a semantic criterion of equal relevance to female literate and illiterate subjects of southern Portugal and asked the participants to name things one can buy at the supermarket. The relevance of this criterion springs from the fact that almost all of the individuals we investigate do the major part of their regular shopping at supermarkets and at comparable levels over time. Reis, Guerreiro et al. (2001; 2003) found no significant difference between illiterates, subjects with 4 years of education, and subjects with more than

4 years of education. Silva et al. (2004) compared the performance of the same illiterate and literate subjects on two time-constrained semantic fluency tasks, the first using the semantic category of food items (supermarket fluency task) and the second, animal names (animal fluency task). The literate and illiterate group performed equally on the supermarket fluency task, while the literate subjects were significantly better on the animal fluency task. The equal supermarket fluency performance excludes a simple explanation for the performance differences on the animal fluency task in terms of general factors such as for example cognitive speed. Instead, the interaction between literacy and semantic criterion can be explained in terms of similarities and differences in shared cultural background. Thus, significant educational effects may or may not be observed depending on the choice of semantic criterion, and more generally this emphasizes the importance of developing instruments that are free of educational and cultural biases when investigating cognition.

SHORT-TERM WORKING MEMORY AND PHONOLOGICAL PROCESSING

As a general background to the following subsections, we note that repetition of pseudowords and digit span tasks are considered to be good measures of verbal working memory capacity. These measures have been shown to correlate with reading achievements in children (Baddeley et al., 1998; Gathercole & Baddeley, 1995). Additional research also points toward a role of verbal working memory and the efficiency of phonological processing in relation to reading skills (Brady, 1991; Goswami & Bryant, 1990; Ziegler & Goswami, 2005). Verbal short-term working memory is a system subserving the representation and on-line processing of verbal information. In the Baddeley-Hitch model, one role of the phonological loop, a subsystem for short-term storage of phonologically represented information, is to store unfamiliar sound patterns. This suggests that the phonological loop might serve as an integral part of a learning device for spoken and written language acquisition (Baddeley et al., 1998).

Several researchers have investigated the relationship between reading and meta-linguistic awareness, including so-called phonological awareness (e.g., Morais, 1993). With respect to phonological awareness this research has indicated that illiterate subjects have some difficulty in dealing with tasks requiring explicit phonological processing. For example, the results of Morais et al. (1979) showed that illiterate subjects found it more difficult to add or remove phonemes at the beginning of words as well as pseudowords. One may ask to what extent these tasks are equally natural to literate and illiterate individuals (i.e., of similar ecological relevance) and thus complicating the interpretation of these findings.

Generally speaking, it is still unclear what type of relation exists between phonological processing, verbal working memory, and the acquisition of orthographic knowledge. Moreover, it appears that the phonological processing difficulties in illiterate subjects are not limited to phonological awareness per se but involve aspects of sub-syllabic phonological processing as well as skills related to verbal working memory (e.g., phonological recoding in working memory). In the following subsections, we will review some results on short-term memory span, pseudoword processing, and word awareness in sentence context.

DIGIT AND SPATIAL SPAN

Several studies have suggested that there is a difference in digit span between literacy groups (e.g., Ardila, Rosselli, & Rosas, 1989; Reis, Guerreiro, Garcia, & Castro-Caldas, 1995). However, Reis et al. (2003) showed that the difference in digit span is not a simple effect of literacy as such. Instead, digit-span seems to be dependent on the extent of formal education: illiterate participants had a mean digit span of 4.1 ($\pm$ 0.9), significantly below literate digit span; but, also literate subjects with 4 years of education (5.2 $\pm$ 1.4) performed significantly below the literate subjects with 9 years of education (7.0 $\pm$ 1.8). Thus it appears that education more generally contributes to the observed difference (overall effect $p < .001$). In a recent follow-up study we compared literate and illiterate participants directly on the digit span and spatial span sub-tasks of the Wechsler Memory Scale (III revision). Consistent with the results just described there was a significant difference between literacy groups on the digit span ($p = .004$) but there was no significant difference on the spatial span task ($p = .3$). These results suggest that illiterate subjects have a lower verbal span compared to literate subjects, while this is not the case for spatial span. For example, it is possible that the phonological working memory representations are in some sense more effective in literate compared to illiterate individuals (Petersson & Reis, 2006).

WORD AND PSEUDOWORD PROCESSING

Reis and Castro-Caldas (1997) concluded that illiterate individuals performed similarly to literate individuals on word repetition, whereas there was a significant difference on pseudoword repetition (literate > illiterate). We have suggested that this is related to an inability to handle certain aspects of sub-syllabic phonological structure and indicates that the phonological representations or the processing of these representations are differently developed in the two literacy groups (Petersson et al., 2000; Petersson et al., 2001).

Alternatively, the system for orthographic representations may support phonological processing as an auxiliary interactive processing network (Petersson et al., 2001); see Olson (1996) for a theoretical perspective. This latter possibility suggests that there might a bi-directional reciprocal influence between orthography and phonology; that is, orthography ↔ phonology rather than orthography → phonology or phonology → orthography; not only do literate subjects have access to additional representational means (orthography) but aspects of the phonological representation itself might be modified by reading acquisition, along similar lines as the phonological grain size theory of Ziegler & Goswami (2005).

Because several aspects of auditory-verbal language may differ between literate and illiterate individuals, it is of interest to isolate the different sources contributing to these differences in phonological processing. In particular, it is important to study the differences in phonological processing relatively independent of lexicality effects (e.g., vocabulary size and frequency effects) as well as articulatory mechanisms. In order to do so, we used an immediate auditory-verbal serial recognition paradigm (Gathercole, Pickering, Hall, & Peacker, 2001) in a recent follow-up study (Petersson et al. 2004). Immediate serial recognition is independent of articulatory speech output. In addition, serial recognition of pseudowords is (relatively) independent of lexicality effects. In this experiment we compared illiterate and literate subjects on immediate recognition of lists of 3 CVCV-syllable items (C = consonant, V = vowel). The lists varied in lexicality (words/pseudowords) and phonological similarity (dissimilar/similar). The participants were asked to judge whether two lists (presented one after the other) contained items presented in the same or different order. Group comparisons showed significant differences: the literate group performing better than the illiterate, in all conditions (pseudoword/dissimilar, $p < .001$; pseudoword/similar, $p = .03$; word/similar $p = .003$), except for phonologically different words ($p = .2$). Of the four conditions, the phonologically different word condition is of course the easiest to handle from a phonological point of view. Words are more familiar than pseudowords and the phonological contrast is greater in the different compared to the similar condition. These results are thus consistent with the differences in pseudoword repetition and digit span performance and further support the idea that there are differences in verbal working-memory capacity and phonological processing between the two literacy groups. In addition, the results on immediate serial recognition suggest that these differences are (relatively) independent of lexicality effects, articulatory organization (e.g., output phonology), and other speech output mechanisms.

WORDS IN SENTENCE CONTEXT

Little is known about how adult illiterate subjects perceive words in a sentence context. Awareness of words as independent lexical units has been investigated in children, both before and after reading acquisition (e.g., Barton, 1985; Hamilton & Barton, 1983; Karmiloff-Smith et al., 1996), and also in illiterate adults (Cary & Verhaeghe, 1991). The results show that explicit knowledge of words as independent lexical units is dependent on literacy. Cary & Verhaegh (1991) suggested that the difficulty for illiterate subjects is to efficiently identify closed-class words because of their relative lack of semantic content. However, given the prominent syntactic role of closed-class words in sentence processing, including sentence comprehension, and the fact that illiterate and literate individuals acquire spoken language on similar terms, we were interested in whether the effects related to closed-class words could be given a phonological explanation. In two recent studies we revisited these issues (Mendonça et al., 2003; Mendonça et al., 2002). In both studies, we investigated the awareness of words in sentence context with the aim of clarifying the role of literacy in the recognition of words as independent lexical units and the possible relation to the known phonological processing characteristics of illiterate subjects. We presented short sentences that varied in their constituent structure in random order to the participants. All determiners, prepositions, pronouns, and adverbs were included in the closed-class category. We divided this class into phonologically stressed and non-stressed words, where the latter are characterized by the absence of a stressed vowel; subjects were instructed to attentively listen to the sentences, to immediately repeat them, and to identify its constituent words. The results of both studies showed that there was no significant difference in sentence repetition, and consistent with previous findings, the literate segmentation performance was significantly better than the illiterate (see Petersson & Reis, 2006 for further details). In particular, the illiterate group showed a specific pattern of merging of words or "clitization" (or "blending of words"). There are very few mergers between the major syntactic constituents, meaning that illiterates are sensitive to the major syntactic structure of the sentence, while increasing rates of mergers were observed within phrase internal constituents. Comparing the stressed and the non-stressed closed-class words (Mendonça et al., 2003) showed that mergers related to closed-class words was observed significantly more often with non-stressed as compared to stressed closed-class words in the illiterate group ($p < .001$).

Overall then, the present results corroborate previous suggestions that recognition of words as independent phonological units in sentence context depends on literacy. However, our results show that the segmentation failures did not distribute evenly over closed-class

words (not even within sub-types) but occurred more often with phonologically non-stressed than phonologically stressed closed-class words. The illiterate subjects are thus more sensitive to phonologically stressed closed-class words which they are able to efficiently segment. We suggest that illiterate segmentation performance is closely related to sentence internal prosody and phonological stress. Thus, the difficulty seems to be a phonological phenomenon rather than related to lexical semantics. In addition, the "clitization" phenomenon seems not to be related to phrase structure per se, since the illiterate group respected phrasal boundaries; blending mainly occurred within phrases and rarely across phrasal boundaries or boundaries between major sentence constituents. A contributing factor to segmentation difficulties may be verbal working-memory capacity, since the performance of the illiterate group increased from the start to the end of sentences. In other words, also the linear sentence position play a role. Thus, illiterate sentence segmentation appears to depend on factors related to phonology, syntactic structure, and linear position, and not on factors related to lexical semantics.

SEMANTIC INTRUSIONS AND THE AWARENESS OF PHONOLOGICAL FORM

Kolinsky, Cary, and Morais (1987) investigated the notion of phonological word length in literate and illiterate subjects. Even when explicitly asked to attend to the abstract phonological properties of words, the illiterate group still found it difficult to ignore their semantic content and thus failed to inhibit the intrusion of semantic information when attempting to solve the task based on a form criterion. Similar findings related to the processing of meaning has been reported in various experimental settings (Reis & Castro-Caldas, 1997; Silva et al., 2004). For example, Reis and Castro-Caldas (1997) showed that illiterate individuals exhibit greater difficulty on tasks that focus on formal rather than substantive aspects of the stimulus material (e.g., phonological vs. semantic aspects of words), findings which results have been replicated in a Greek population (Kosmidis, Tsapkini, & Folia, 2007, in press; Kosmidis, Tsapkini, Folia, Vlahou, & Kiosseoglou, 2004). Kolinsky and colleagues (1987) suggested that learning to read plays an important role in the development of the ability to focus on the phonological form of words.

In a recent experiment (Reis, Faísca, Mendonça, Ingvar, & Petersson, 2007), literate and illiterate participants listened to words and pseudowords during a phonological ("sound") length decision task, in which the participants were asked to decide which item in a pair was the longest in phonological ("sound") terms. In the word condition, we manipulated the relationship between word length and size of the denoted object, yielding three sub-

conditions: (1) *Congruent* - the longer word denoted the larger object; (2) *Incongruent* - the longer word denoted the smaller object; (3) *Neutral* - only phonological length of the words varied, denoting objects of similar size. Pseudoword pairs were constructed based on the real-words pairs by changing the consonants and maintaining the vowels as well as length. Two effects were of interest in the results. First, the literate subjects showed no effect of semantic interference whereas this was clearly the case in the illiterate group. Secondly, while the literates performed at similar levels on words and pseudowords, the illiterate group performed significantly better on pseudowords compared to words. In fact, the mean performance in the pseudoword condition was slightly better than in the neutral word condition. These results suggest that the illiterate subjects show a greater difficulty in inhibiting the influence of semantic interference, the intrusion of lexical semantics in the decision process.

CONCLUSION

In the first part of this chapter, we reviewed a modified Marr's framework: 1) the *cognitive level* - a formal theory of structured cognitive states and the cognitive transition system, which specifies the transitions between cognitive states and the results of information processing; 2) the *dynamical system level* - given a formal cognitive theory, a state-space is specified and processing is formulated in terms of a dynamical system which embeds the system specification at the cognitive level; 3) the *implementation level* - given a dynamical system, this level specifies the physical hardware implementation of the dynamical system (e.g., a neural network). We also outlined a framework for investigating developmental learning system as coupled dynamical systems and indicated the extreme complexity involved in attempting to understand the human brain from a cognitive neuroscience point of view. We concluded that, in a very important sense, most of the empirical and theoretical work necessary for a deeper understanding of human cognition remains to be pursued in order to specify integrated models of cognition, development, and learning.

In the second part, we briefly discussed how cognitive states, viewed as physical states, and operations on these states (i.e., information processing) can be empirically characterized with functional neuroimaging techniques as well as behaviorally, and in the final part we took the view that the educational system can be viewed as an institutionalized process for structured cultural transmission. The study of illiterate subjects and their literate controls represents one approach to investigate the interactions between neurobiological and cultural factors on the outcome of learning and cognitive development. The results reviewed here suggest that literacy influence important aspects of cognition, most prominently the

processing of sub-syllabic phonological structure, verbal working memory, and object recognition/naming. Literacy and education also influence corresponding structural and functional properties of the brain. Taken together, the evidence provides strong support for the hypothesis that certain functional properties of the brain are modulated by literacy and formal education. Literacy and formal education influence the development of the human brain and its capacity to interact with the environment. This includes the culture of the individual who, through acquired cognitive skills, actively can participate in, interact with, and contribute to, the process of cultural transmission.

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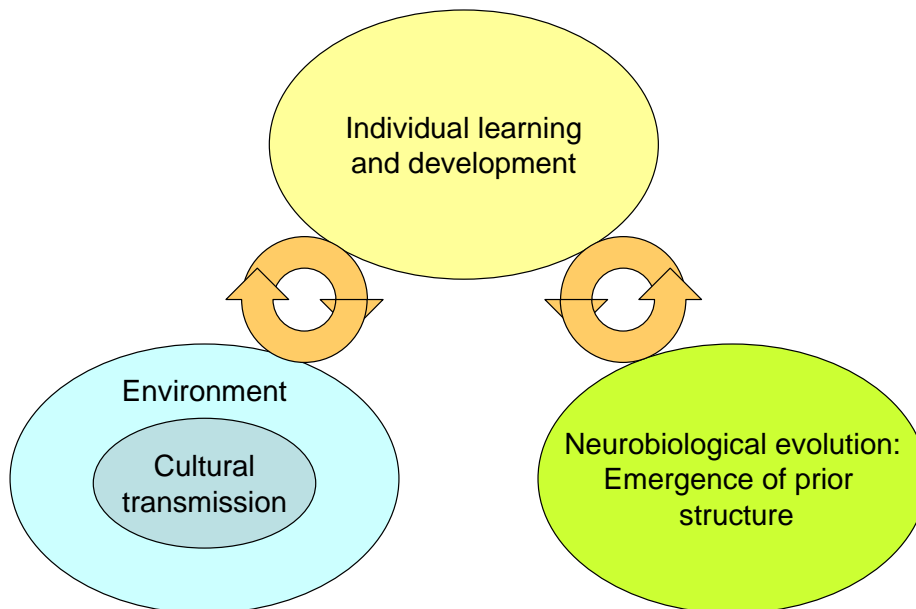
FIGURE LEGENDS

Figure 1. An adaptive cognitive system situated in the context of its evolutionary history and its current environment. Neurobiological systems are naturally evolved information processing (cognitive) systems. In order to understand the significance of their different features it is necessary to take into account both their individual developmental (ontogenesis) as well as their evolutionary histories (phylogenesis). Neural systems have evolved under tight energy, space, and real-time processing constraints. With respect to perception, for example, the characteristic time-scale of processing must match that of the external world, and similarly, for output control, the characteristic time-scale of motor output must match the time it takes to organize a coordinated response that is behaviorally relevant. Moreover, when

the outputs from different processing components need to be integrated, then the time-scales of the various processors involved must also match and necessary memory constraints must be met. There are also more general constraints in terms of available energy turnover, the physical and biochemical infrastructure, as well as spatial constraints. It seems safe to assume that these types of general constraints must have had an important influence on the brain from an implementation point of view. There are good reasons to believe that the nervous system is not fully specified at a phylogenetic (i.e., genetic) level – the existence of learning and adaptation speaks clearly on this issue – it would also seem too restrictive, ineffective, or too costly to pre-specify every detail of the functional organization of the brainl. Instead, ontogenetic development and learning represent viable complements.
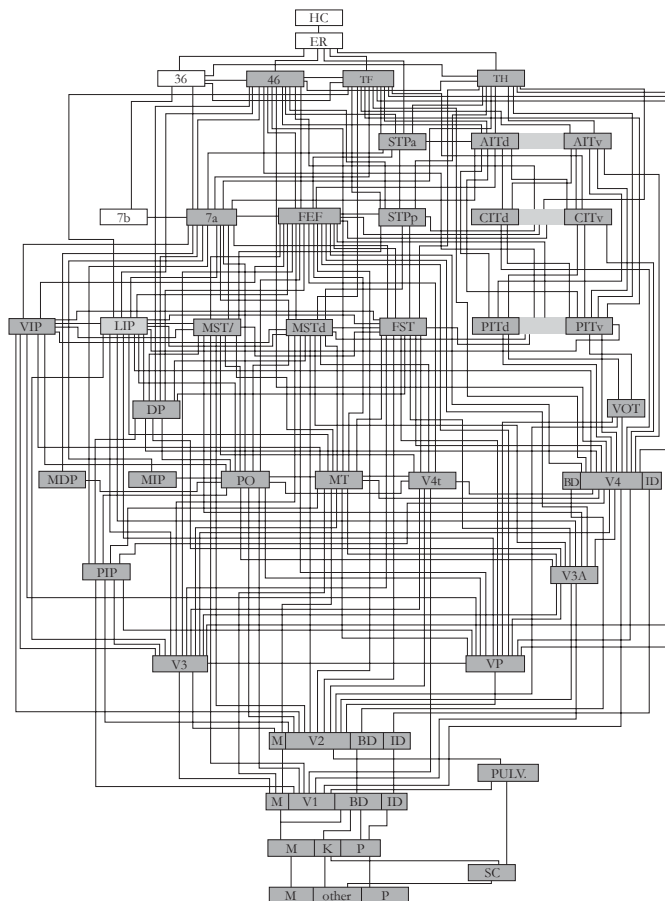

Figure 2. The structural organization of the human brain. Brain connectivity resembles a tangled hierarchically structured and recurrently connected network composed of different functionally specialized brain regions, which in turn consists of several types of processing elements (neurons) and synaptic connections between neurons (Felleman & Van Essen, 1991; Shepherd, 1997). This processing infrastructure allows for a rich non-stationary class of non-

linear dynamical models. (Adapted from Felleman & van Essen, 1991; courtesy of Frauke Hellwig).

Information processing systems

Environment

Sensory Input

Motor Output

Information Processing
$T: \Omega \times \Sigma \rightarrow [\Omega, \lambda]$
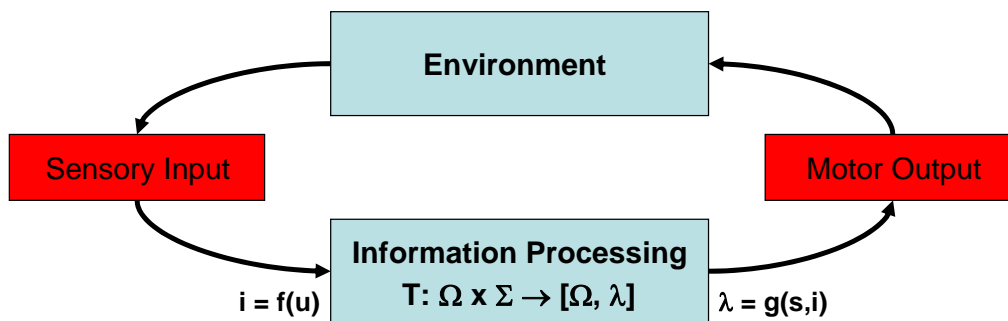
$i = f(u)$

$\lambda = g(s,i)$

Figure 3. Information processing systems. Cognition is equated with internal information processing in interaction with the environment, the so-called perception-action cycle. Here the cognitive system is portrayed as interfacing with the external environment through sensory and motor interfaces. However, the processing (sub-)system can equally well be viewed as interfacing with other sub-systems. The space of internal states Ω contains individual cognitive states, s (i.e., $s \in \Omega$; reads: s belongs to Ω). The processing of information is governed by dynamical principles, T, which are represented as a transition function/relation $T:\Omega x\Sigma \rightarrow \Omega$: Given an internal state $s \in \Omega$ and input u (here appropriately transformed according to $i = f(u) \in \Sigma$ by some transduction mechanism), T specifies (deterministically/indeterministically) a new internal state $T(s, i) \in \Omega$, while output λ ($\lambda \in \Lambda$, the space of outputs) is generated optionally according to a suitable output transformation $\lambda = g(s, i)$, which for convenience can be taken to be a component of T (i.e., T extended with $\lambda:\Omega x\Sigma \rightarrow \Lambda$ according to $T \leftarrow [T, \lambda]$). At processing time-step t, the system receives input i(t) in state s(t), then the system changes state into $s(t+\Delta t)$ and outputs $\lambda(t+\Delta t)$ according to:

$$[s(t+\Delta t), \lambda(t+\Delta t)] = T[s(t), i(t)] \qquad [1]$$

Equation [1] describes a forced (input driven) discrete-time dynamical system. The memory organization of the system has not been explicitly described here (cf. **Figure 4** and **5**). The characteristics of the memory organization is crucial because these determine in important respects the expressive power of the processing architecture (for a brief review see Petersson (2005b) or alternatively, Savage (1998); Wells (2005)).
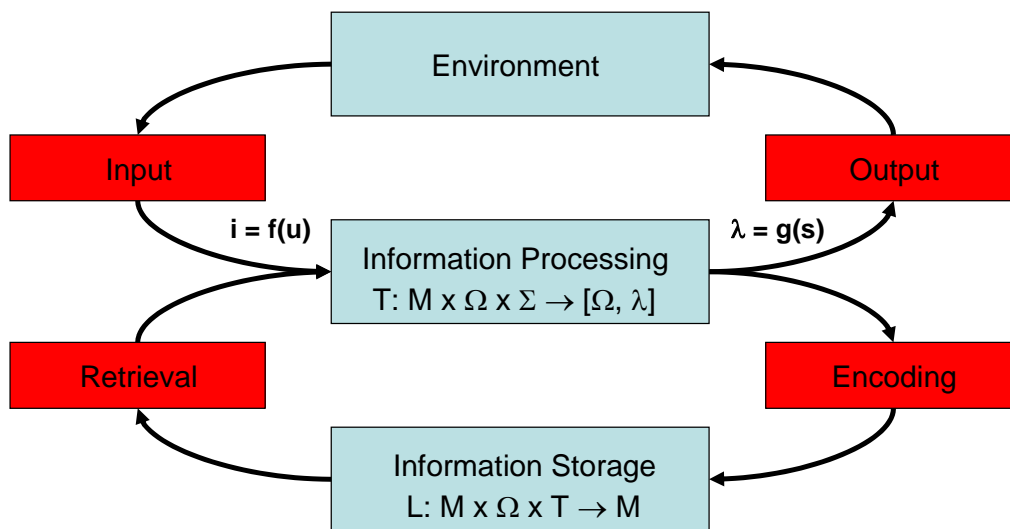
Adaptive Information Processing Systems

Figure 4. Adaptive information processing systems. Given a cognitive system or a cognitive module C, we can conceptualize the system development as a trajectory in its accessible model space M = [m| m can be instantiated by C] driven by C's interaction with its environment, in conjunction with innately specified developmental processes (**Figure 1**). At any point in time, t, C is in a given state $m_C(t)$ (i.e., C instantiates the model $m_C(t)$). If we suppose that C incorporates an innately specified prior structure, we can capture this by the notion of a structured initial state, $m_C(t_0)$. Thus, as C develops, it traces out a trajectory in M determined by its adaptive dynamics L according to:

$$m_C(t+\Delta t) = L(m_C(t), s(t), t) \qquad [2]$$

where the explicit dependence on time in L captures the idea of an innately specified developmental process (maturation) as well as a possible dependence on the previous developmental history of C. If C and L are such that it (approximately) converges on a final model $m_C[F]$, this will characterize the end-state of the developmental process reached after time Δt_F, that is, $m_C(t_0 + \Delta t_F) \approx m_C[F]$. Within this adaptive framework, m_C determines the transition function T in the following sense: T can be viewed as parameterized by m_C (i.e., T is a function of m_C) according to $T = T[m_C]$, and equation [1] of **Figure 3** needs to be modified according to:

$$[s(n+1), \lambda(n+1)] = T[m_C][s(n), i(n)] \qquad [1']$$
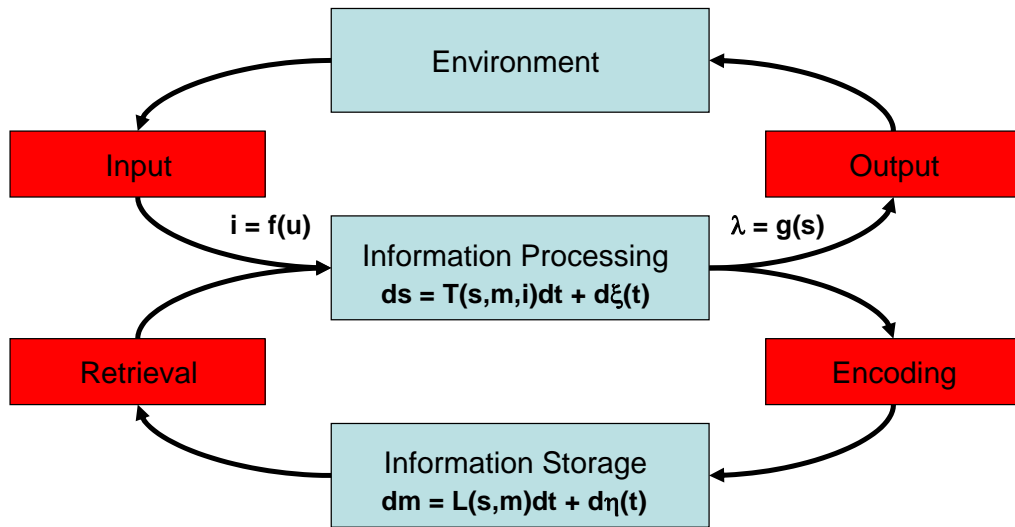
(cf., Petersson, 2005a).

Adaptive Dynamical Systems

Figure 5. Adaptive dynamical systems. A cognitive processing system C with adaptive properties is specified as an ordered triplet, C = <functional architecture, representational dynamics, learning dynamics>; (1) the *functional architecture* is a specification of the structural organization of the systems; (2) the *representational dynamics* includes a specification of a state-space, Ω, of state variables, s, carrying/representing information (s $\in$ Ω; e.g., membrane potentials), and dynamical principles, T (i.e., T:ΩxMx$\Sigma \to \Omega$), governing

the active processing of information; and (3) the *learning dynamics* includes a specification of learning (adaptive) variables/parameters, m (e.g., synaptic parameters), for information storage (memory formation) and dynamical principles, L (i.e., a "learning algorithm"; e.g., co-occurrence or covariance based Hebbian learning) governing the temporal evolution of the learning variables in the model space M (m $\in$ M). The temporal evolution of the adaptive parameters depends on the active processing of information and the learning dynamics is commonly conceived of as taking place on a slower (longer) characteristic time-scale than that of the representational dynamics. To be more explicit, this can for example be formulated within the framework of multivariate stochastic differential/difference equation (e.g., Øksendal, 2000), here with additive noise processes $\xi(t)$ and $\eta(t)$:

$$ds = T(s,m,i)dt + d\xi(t) \tag{3}$$

$$dm = L(s,m)dt + d\eta(t) \tag{4}$$

where i is the input representation the system receives (i.e., i = f(u)) and the output λ is a function of s (i.e., λ = g(s)). Note that the representational dynamics corresponds to equation [3], while the learning dynamics corresponds to equation [4]. These equations represent a system of coupled stochastic differential/difference equations, which allows the information processing to interact with the learning dynamics. For example, equation [3] and [4] can be related to the interaction between the perception-cognition-action and encoding-storage-retrieval cycle, respectively, where [3] is related to the active processing of information in the perception-cognition-action cycle and [4] is related to the encoding-retrieval cycle. Note also that [3] and [4] corresponds directly to the classical picture given by [1'] and [2] of **Figure 4**.
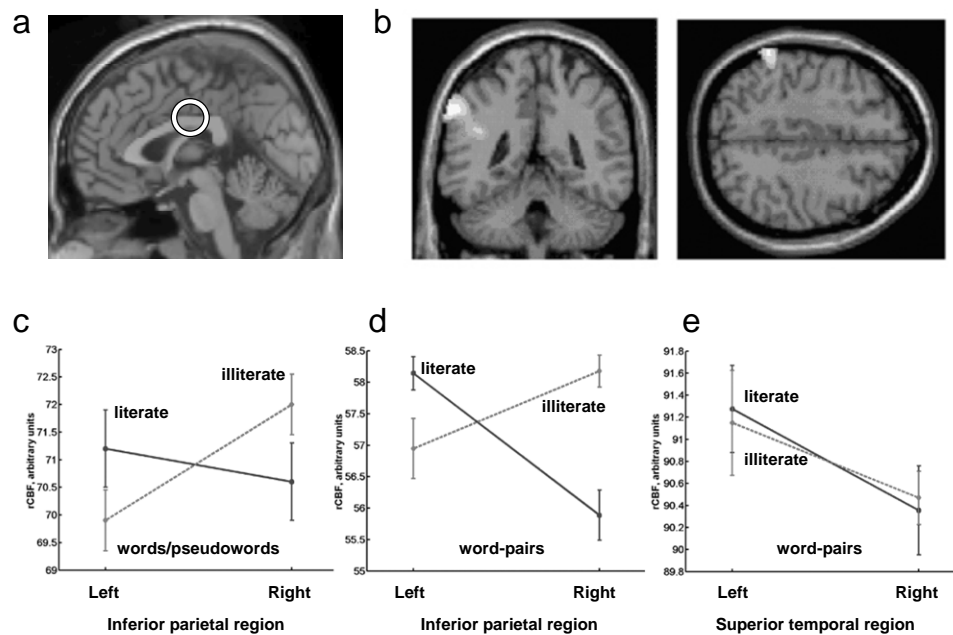
Figure 6. (a) Morphological investigations of structural MR data suggest that the local thickness of the corpus callosum (circle) is thinner in illiterate compare to the literate subjects ($p < .01$) in the posterior mid-portion. **(b)** Hemispheric differences (left vs. right) in activations levels between literacy groups in the inferior parietal region (Brodmann's area 39/40; literate > illiterate). **(c)** In experiment 1 the participants listen to and repeated words and pseudowords. The diagrams show the level of left- and right activation levels (regional cerebral blood flow, arbitrary units) as a function of literacy group (illiterate: dashed). Differences averaged over conditions $p = .009$ (words: $p = .017$; pseudowords: $p = .006$). **(d)** In experiment 2 the participants were listening to and encoded word-pairs. Again we observed left-right activation differences (nearest supra-threshold cluster test, $p = .029$, corrected) between literacy groups in the inferior parietal region (Brodmann's area 39/40). **(e)** To test the specificity of these left-right results with respect to the inferior parietal cortex, we also investigated the superior temporal region (BA 22/41/42) in the second experiment. The results showed that both literacy groups were similarly left lateralized in this region indicating that the functional lateralization of early speech related brain regions does not depend on literacy.