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Modelling the Developing Mind: From Structure to Change

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Abstract

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This paper presents a theory of cognitive change. The theory assumes that the fundamental causes of cognitive change reside in the architecture of mind. Thus, the architecture of mind as specified by the theory is described first. It is assumed that the mind is a three-level universe involving (1) a processing system that constrains processing potentials, (2) a set of specialized capacity systems that guide understanding of different reality and knowledge domains, and (3) a hypecognitive system that monitors and controls the functioning of all other systems. The paper then specifies the types of change that may occur in cognitive development (changes within the levels of mind, changes in the relations between structures across levels, changes in the efficiency of a structure) and a series of general (e.g., metarepresentation) and more specific mechanisms (e.g., bridging, interweaving, and fusion) that bring the changes about. It is argued that different types of change require different mechanisms. Finally, a general model of the nature of cognitive development is offered. The relations between the theory proposed in the paper and other theories and research in cognitive development and cognitive neuroscience is discussed throughout the paper.

Modelling the Developing Mind:
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By definition, developmental psychology is a science of change. However, it is recognized nowadays (e.g., Demetriou, 1993; Siegler, 1995) that despite its definitional objective, developmental psychology is still impressively poor in capturing, modelling, and explaining change. Although we do have a rather accurate knowledge about the global timing of developmental changes in various dimensions of behavior and experience, such as cognition and thinking, emotions, social interactions, and language (see Demetriou, Doise, & van Lieshout, 1998), we still do not know very well either the causes that produce the changes or the mechanisms that bring the changes about. Also, there is no general agreement about the nature of developmental change as such. That is, the field is still divided between the camp of those who believe that change is basically stagelike and discontinuous (e.g., Case, 1992; van Geert, 1994) and those who believe that development is smooth and continuous (e.g., Siegler, 1995, 1996). In conclusion, there is no agreed-on model of change in developmental psychology. Our aim in this paper is to contribute to the development of such a model. In pursuit of this aim, we propose a general framework for specifying and modelling change in the development of the human mind. This framework will be based primarily on recent research and theorizing on cognitive development.

The Minimum Mental Architecture for the Development of Mind

Piaget (1973, 1975) maintained that only structure is changing in human development, whereas the basic mechanisms of development remain invariant throughout the human life. The reader is reminded that, according to Piagetís theory, the same equilibration process, which is driven by the functions of accommodation and assimilation, brings about changes in the coordination of mental operations which result in the *structures dí ensemble* which characterize his well known stages of cognitive development. We will argue below that there may indeed be changes in the organization of mental operations and that there are developmental mechanisms which remain invariant. We will also argue that the basic architecture of mind, which involves mental operations oriented to the environment and operations oriented to the self, is present from early in life, if not from the beginning, and that this architecture is a necessary precondition of developmental change. Moreover, we will also argue that development brings about changes in the mechanisms of change themselves. These changes in the mechanisms of change explain how mind is raised to ever higher levels of functioning.

The kinds of change that any system can undergo are constrained by its structure and the functions that this structure was designed to serve, on the one hand, and by the environment and the input it provides, on the other. Thus, if we are to understand the development of the human mind we would have to specify its minimum architecture and its primary functions which define the dimensions along which the mind develops, the fundamental causes which fuel its development, and the basic mechanisms that are responsible for the implementation of change. Mind is a thinking machine which evolved so as to be able to understand states and change in the world, itself included. Thus, its architecture has to involve both world-directed and self-directed "organs" and ensuing functions. In the pages below, we will first summarize a theory about the architecture of mind that directly deals with these issues. This is the theory proposed by Demetriou and colleagues (Demetriou, 1993, 1998a, 1998b; Demetriou & Efklides, 1994; Demetriou, Efklides, & Platsidou, 1993a; Demetriou, Kazi, & Georgiou, submitted-a; Demetriou, Kazi, Platsidou, Sirmali, Kiosseoglou, submitted-b). Then, we will explore the implications of this theory for developmental change. The relations between this theory and the work of other workers in cognitive development and developmental neuroscience will also be discussed.

According to this theory, the architecture of the human mind includes two basic hierarchical levels of knowing. The first of these involves environment-oriented systems, the second involves system-oriented constructs. At the intersection of these two levels there also seems to be a functional system that defines the activation and the interaction between the two knowing levels. It also needs to be noted that the processes and structures in each of the levels may themselves be hierarchically organized. This architecture has already been extensively explained and empirically substantiated elsewhere (Demetriou & Efklides, 1985, 1989; Demetriou et al., 1993a; Demetriou, Efklides, Papadaki, Papantoniou, & Economou, 1993b; Demetriou, Pachaury, Metallidou, & Kazi, 1996; Demetriou, Platsidou, Efklides, Metallidou, & Shayer, 1991; Demetriou et al., submitted-b; Loizos, 1992; Shayer, Demetriou, Pervez, 1988). Thus, in the section below a brief summary will only be given with an emphasis on those aspects of architecture that are necessary for the discussion of the mechanisms and nature of development to follow.

Environment-Oriented Systems

The first of the two knowing levels involves systems addressed to the environment. Thus, the input to this level is information coming from the environment and its output are actions, overt or covert, directed to the environment. Empirical research in our laboratory led to the identification of the following systems: categorical, quantitative, causal, spatial, propositional, social thought, and drawing. These systems are domain-specific, procedurally-specific, and symbolically biased. That is, each of these systems is a domain of thought that specializes in the representation and processing of a particular type of relations in the environment. As a result, each of these systems involves mental operations and processes which reflect the peculiarities of the elements and relations which characterize the domain of reality to which it is oriented. Thus, we call these domains of thought *Specialized Capacity Systems* (SCSs)[1].

Therefore, the different SCSs are characterized by different properties in as far as all three important aspects of problem solving are concerned. That is, (a) in classical terms (Newell & Simon, 1972), the representation of the problem space (for example, some problems require a binary propositional representation whereas some other problem require a holistic-imaginal representation), (b) the specification of information units which constitute a given problem (for example, some problems involve arithmetic units whereas some other problems must be defined in relation to the coordinates of three-dimensional space, and (c) the specification of the operations which must be executed on these units (for example, some problems require the conjunction or the disjunction of propositions in inference patterns of the "if p then q" or the "either p or q" type, whereas some other problems require the mental rotation of a given image or object).

Finally, each SCS is biased toward those symbolic systems which are more conducive than others to the representation of its own properties and relations and to the efficient application of its own operating processes on the elements of the reality domain concerned. In other words, the SCSs are considered to be fields of thought that preserve the organizational and dynamic peculiarities of the different fields of reality which made their evolution necessary. As such, each of these systems is a dynamic, multilayered, and multidimensional entity that involves three main types of elements or components.

First, each SCS involves ever present kernel elements or core operators that match the defining elements and relations of an SCS's field. For instance, depth perception, subitization, and the perception of physical transmission of movement between objects which are in visible contact with each other, such as a walking mother pushing a baby carriage, may be kernel elements of the spatial, the quantitative, and the causal SCS, respectively, at the level of perception. Also, the various SCSs involve core operators at the level of action itself. In fact, these may be more important as starting points of cognitive development than kernel elements at the level of perception.

Orientation in space as a result of oneís movement in a given environment may be taken as a core operator for the spatial SCS. Oneís own actions on the numerosity of things, such as adding or taking things away from a set, and the ensuing representations may be taken as examples of core operators for the quantitative SCS. Finally, oneís own exploratory actions on the behavior of persons and things and the ensuing representations may be taken as core operators for the causal SCS.

We propose that the kernel elements of each SCS are innate, present at birth or directly derived from maturational changes early in life, and informationally encapsulated in the Fodorian sense (Fodor, 1983). These components may err in their application on their domains but their errors are illusions in the classical sense of the term. For instance, depth perception is deceived in the set-up of Gibson and Walkís (1960) visual cliff. Subitization may easily be deceived about the numerosity of a set of objects if the distance between them exceeds a certain range. Likewise, the perception of the physical transmission of movement may easily be deceived when there are more than one possible causal agents. For instance, if both parents touch on the handle of the baby carriage, perception cannot tell who is actually the cause of the carriageís movement. It is noteworthy that recent research on animal cognition (Gallistel, 1993) provided strong empirical evidence indicating the presence of these modules qua modules in many different animals, such as the ant, the bee, and the rat, let alone the primates.

Second, the systems also involve rules, processing skills, and operations that evolve as a result of the application of the core operators on the environment over time. In fact, we have shown empirically that each SCS is a complex network of component processes and operations which complement each other in the representation and processing of the different aspects of the reality domain to which each SCS is affiliated. For instance, strategies for effecting mental rotations, coordination of perspectives, and orientation in space may be taken as examples of component processes involved in the spatial-imaginal SCS (Demetriou et al., 1993a, Loizos, 1992).

Arithmetic operations and proportionality may be taken as examples of the quantitative-relational SCS (Demetriou et al., 1991; Demetriou et al., 1996). Hypothesis formation, experimentation, and model construction, which integrates hypotheses with the results of experimentation into interpretative frames or theories, may be considered as examples of the causal-experimental SCS (Demetriou et al., 1993a; Demetriou et al., 1993b).

Finally, each of the SCSs involves products of the past operation of the core elements, the rules, and the processing skills involved in it. These products are conceptions and beliefs about the field of reality each of the SCSs is affiliated to and they constitute the person's knowledge base about this field. Research and theorizing on the so called foundational theories that persons hold for the physical, the biological, and the social world (Wellman & Gelman, 1992) and about conceptual change with regard to these conceptual domains (Carey, 1985; Vosniadou, 1994; Wellman, 1990) is related more to this level of the organization of each SCS than to the two lower levels described above. That is, in the context of the present theory, concepts, beliefs, and foundational theories are to be regarded as the result of the ongoing application of the various SCSs on the different aspects of the world which generates information about the world which is stored for future use. It is also recognized that the constructs at this level may frequently result from the joint application of more than one SCS. For example, theories about different aspects of the world may involve spatial, causal, and quantitative components. In fact, misconceptions about the world are frequently due to the mixing up of information coming from different SCSs. The geocentric model of our planetary system, which dominated human thought for ages, is a telling example. Obviously, this model is due to the dominance of spatial-visual representation of the relations between the sun and the planets over the weaker but more relevant causal and quantitative information that would have to be abstracted by the corresponding SCS.

We have employed a number of different methods to substantiate the assumptions about the environment-oriented systems. Specifically, we conducted a large number of factorial studies in order to test the assumptions about the internal organization of the SCSs into different components and about the relations between different SCSs. In general, the studies that aimed to map the composition of an SCS in detail involved many tasks addressed to the various components presumably involved in the SCS concerned. For instance, the studies addressed to the quantitative SCS involved tasks which required the ability to execute the arithmetic operations in combination to each other, algebraic ability, and proportional reasoning (Demetriou et al., 1996; Demetriou et al., 1991). The studies addressed to the causal SCS involved tasks which required combinatorial thought, the ability to design experiments, and the ability to interpret evidence in relation to hypotheses (Demetriou et al., 1993a; Demetriou et al.,

Insert Figure 1 about here

1993b). The studies addressed to the spatial SCS involved tasks which required mental rotation, integration of components into an image, and coordination of perspectives (Demetriou & Efklides, 1989; Demetriou et al., 1993a; Loizos, 1992). The studies addressed to the verbal SCS involved tasks tapping various logical relations, such as modus ponens, modus tollens, conjunction, disjunction, etc. (Kargopoulos & Demetriou, 1998; Efklides, Demetriou, & Metallidou, 1994). The studies that aimed to specify the relations between SCSs involved at least two components of at least two different SCSs (Demetriou & Efklides, 1985, 1989; Demetriou et al., 1993a, submitted-b). Panel A of Figure 1 shows the general model that is able to account for performance attained in these studies. That is, the model involves constructs (or factors) that stand for (1) the SCSs themselves, which integrate the SCS-specific core elements (not shown in the Figure), (2) higher-order constructs, which integrate the SCSs into broader realms of thought, and (3) a general construct that stands for the effects exerted on the functioning of the

SCSs by the processing and the hypercognitive system to be described below. It needs to be noted that a particular study need not involve tasks addressed to all of the constructs and relations involved in the model. Instead, it may address parts of this model depending upon its priorities.

Granted, factorial studies are not fully trusted by many developmental and cognitive psychologists. This is due to the view that correlations, which constitute the raw material of these studies, do not necessarily reflect causal relations between the constructs concerned. Moreover, they are sensitive to various adverse influences related to the measurement procedures and the testing conditions that may distort the relations between the constructs under study. To overcome these limitations and provide further support to our proposals about the SCSs, two other kinds of methods were employed, which are very different from the psychometric-like methods of the studies summarized above.

First, in a series of training studies we provided learning experiences directed to one component of one SCS and we looked for transfer to other components both within the trained SCS and in other SCSs. The basic assumption is that the transfer of learning across components within an SCS occurs more easily and to a larger extend than accross components which belong to different SCSs. This is due to the presence of common processes in the various components of an SCS. Thus, improving a process within one component will affect the functioning of other components which involve this process. These studies did show that the positive effects of training do generalize within an SCS but they do not generalize across SCSs. Therefore, these findings do support the assumption about the constructional differentiation between SCSs (Demetriou et al., 1993a, Study 2).

Second, we showed by means of formal analysis that there are kernel elements in each SCS which cannot be formally reduced either to standard logic or to the kernel elements of the other SCSs (Kargopoulos & Demetriou, 1998). Moreover, we also showed that the same logical schema, such as modus tollens or disjunction, is applied differently in the context of different

SCSs, such as the causal, the quantitative, and the spatial (Demetriou, Kargopoulos, & Shayer, in preparation). These findings suggest both that the SCSs involve different inferential mechanisms and make use of the same inferential mechanisms in idiosyncratic ways.

The Hypercognitive System

It was argued above that the SCSs are domain-specific, computationally-specific, and symbolically biased. Obviously, problem-solving creatures other than humans, such as animals and computers, may possess SCS-like systems which are governed by these three principles. However, possession of SCS-like systems is not sufficient to credit these creatures with mind. For this to be possible, a cognitive system must be capable of *self-mapping.* That is, it must be able to record its own cognitive experiences and represent them as different if they differ between each other in regard to domain-specificity, procedural specificity, and symbolic bias. This is the minimum requirement for the construction of a ìtheory of mindî and a self-system that can be used for understanding and regulating oneís own and othersí behavior and problem solving.

Positing this principle implies that creatures capable of self-mapping involve a second-order level of knowing. In our terms, this is the *hypercognitive system*. The input to this system is information coming from the first level (sensations, feelings, and conceptions caused by mental activity). This information is organized into the maps or models of mental functions and the self to be described below. These are used to guide the control of the functioning of the first level. Thus, the hypercognitive system involves self-awareness and self-regulation knowledge and strategies and is conceived as the interface between (a) mind and reality, (b) any of the SCSs or any other cognitive functions, and (c) the processing system to be described below and the SCSs.

We have argued that the hypercognitive system, like the SCSs, is hierarchically organized. That is, it involves working hypercognition and long-term hypercognition. Working hypercognition comprises self-monitoring and self-regulation processes used during on-line problem solving or decision making. These include processes related to the control of attention, allocation of mental resources, selection of problem-specific processes and skills, and evaluation of problem solving or decision making outcomes. Panel B of Figure 1 shows the general flow of processes involved in working hypercognition.

Long-term hypercognition involves models and representations about past cognitive experiences which come as a result of the functioning of on-line self-monitoring and self-regulation. These models involve descriptions about the general structural and dynamic characteristics of the mind. For example, that there are different cognitive functions, such as perception, attention, memory, and different cognitive structures, such as the SCSs described above. Moreover, these models involve prescriptions and rules about the efficient use of the functions. For instance, that excessive information requires organization if it is to be retained in memory or that rehearsal is needed if one is to learn quickly and permanently. Research on theory of mind, (e.g., Flavell, Green, & Flavell, 1995; Fabricius & Schwanenflugel, 1994; Wellman, 1990) and on implicit theories of intelligence (Kazi & Makris, 1992; Sternberg, Conway, Ketron, Bernstein**,** 1981) sheds light on this aspect of long-term hypercognition. Moreover, research on self-evaluation and self-representation in regard to intellectual functioning is related to the evaluative and regulatory aspects of hypercognition (Demetriou et al., submitted-a; Harter, 1990; Nicholls, 1990).

In our research two types of studies were conducted to substantiate the assumptions of the theory in regard to awareness about the mind in general and the cognitive self in particular. In the first type of studies, subjects solved tasks addressed to different SCSs. They were then given descriptions of component processes which, according to the theory, are involved in the processing of each type of tasks and they were asked to rate each of these processes in regard to how much they used them when working on each of the tasks. It was found that, in general, persons associate each of the component processes much more with the tasks to which they are theoretically associated than with any other task. Although this awareness does develop, is present from very early. In one of our studies we were able to show that 4-years-old children are able to differentiate between mathematical and categorization tasks on the basis of the operations involved in them (Demetriou et al., 1993a, Study 3; Kazi, in preparation; Makris, 1995).

In the second type of research, subjects were tested on tasks representing various SCSs and they were also asked to rate themselves on a large number of statements describing several component processes associated with each of the SCSs represented in the task battery. Then it was tested, by means of structural modelling, if the same SCS-like organizations underlie performance itself and self-ascriptions of facility with the various processes. This was indeed found to be the case (Demetriou & Efklides, 1989; Demetriou et al., 1993a; Demetriou et al., submitted-b, Study 1). Panel C of Figure 1 illustrates this finding. That is, that the organization of domains at the level of the hypercognitive system mirrors their organization at the domain of the environment-oriented level itself as this is suggested by performance on tasks representing the various domains.

The Processing System

At the intersection of the environment-oriented and the self-oriented level there is the processing system. In our research, this system was specified in terms of three-dimensions. That is, *speed* (the maximum speed at which a given mental act can be efficiently executed), *control* (the maximum efficiency at which a decision can be made about the right mental act to be executed according to the moment's requirements, as indicated, for instance, by response times to stimuli involving conflicting information), and *storage* (the maximum number of information units and mental acts the mind can efficiently activate simultaneously). In a sense, the processing system may be seen as a dynamic field that is always occupied by elements coming from both of the other hierarchical levels, in proportions which vary from moment to moment. Specifically, the input to this system is environment-relevant information, skills, and processes, which pertain to an SCS, and monitoring, regulation, and evaluation processes, which pertain to the hypercognitive system. These latter processes are responsible for effecting the orchestration and the processing of the former and for the evaluation of the outcome of processing in relation to the goal of processing. We would argue here that working hypercognition is the management system which is responsible for the management of the processing system (Demetriou et al., 1993a).

Therefore, the SCSs, the hypercognitive system, and the processing system are at one and the same time distinct and dynamically intertwined. That is, the SCSs are formulated in response to the structure of the environment and become operative via the processing system and known via the hypercognitive system. The processing system is void if not fed by the SCSs and undirected if not controlled by the hypercognitive system. One might argue that on-line hypercognition carries over to the processing system, so to speak, both the person's personhood and the person's more general views about the mind thereby shaping oneís personal processing style. At the same time, however, the hypercognitive system draws upon and is nourished by the SCSs and is constrained by the processing system in the kinds and the scope of controls it can exercise (Demetriou et al., submitted-b). The double arrows which connect Panel B (working hypercognition and the procesing system) with Panels A (the environment-oriented SCSs) and C (the mental maps that reside at the level of long-term hypercognition) in Figure 1 are intended to stand for these dynamic relations between the three levels of the mind.

A special experimental design was adopted in order to demonstrate our assumptions about the architecture of mind. That is, we used different tasks to address each of the levels and sub-levels of the mental architecture. The tasks addressed to each level were designed so as to require the processes specific to this level and the processes specific to all lower levels.

Thus, at the most basic level, there were tasks which represented only processing speed. Response times to Stroop-like tasks were used as indexes of processing speed. In these tasks the subjects had to recognize a familiar stimulus under conditions of maximum facilitation (for example, they were asked to read a color word printed in the same ink-color). At the next level there were tasks requiring both processing speed and control of processing. Response times to incompatible Stroop-like tasks were used as indexes of control of processing (for example, the subjects had to recognize the ink-color of color words referring to a different color). These conditions were taken to represent control of processing because they require from the subject to inhibit a dominant but irrelevant response in order to emit a weaker but relevant response. At the next level there were the working memory tasks, which, by definition, presuppose both processing speed and control of processing in addition to a storage buffer or function. At the next level, there were SCS-specific tasks which require the application of SCS-specific processes in addition to the processes represented by the three dimensions of the processing system. Finally, there were tasks addressed to oneís model of the cognitive system and oneís cognitive self-image, which evidently require special self-monitoring and self-representation processes on top of the processes associated with all lower levels. The ideal test of the architecture represented by this design would be a hierarchical model that would involve dimensions corresponding to all of the levels specified above. Indeed, this model was found to have an excellent fit in a series of studies both in Greece (Demetriou et al., 1993a, Study 5; Demetriou, Platsidou, & Sirmali, in preparation; Demetriou et al., submitted-b, Study 2; Platsidou, 1993) and China (Platsidou, Demetriou, & Zhang, 1997; Zhang, 1995).

The Origins of Cognitive Change: From Structure to Change

The development of any system implies (i) increasing skill in avoiding errors in its operation, (ii) increasing efficiency in using the system's resources, and (iii) increasing the system's field of operation either through the application of available concepts or skills in new domains or through the construction of new concepts or skills. So defined, development requires the following mechanisms, if it is to occur: (a) a mechanism generating variations or divergence between the momentís goal and the attempted representations or solutions (i.e., a mechanism causing misapplications, errors, inefficient or insufficient operation of the processes already available); (b) a mechanism furnishing criterion representations that may be taken as the basis for the selection of those variations that look closer to the goal; (c) a recording device that can register side-by-side both the criterion states and the alternatives, and (d) a right-and-wrong marking device which can capture the deviations between the criterion states and the alternatives. We suggest that the architecture proposed by the present theory is the minimum architecture needed if all four requirements above are to be satisfied.

Specifically, the mechanism generating variations between the systemís representations or attempted solutions and the goal of the moment is rather easily specified. To a large extent, part of this mechanism resides in the environment itself. Normally, the environment is rarely, if ever, fully identical along time. Thus, variations and divergence between a goal and an attempted solution or interpretation may be justified by slight variations in the information provided by the environment itself at any two points in time. Most importantly, however, this mechanism may be a property of the very nature of the mind itself. For one thing, misencoding, misrecording, or misinterpretation of the information provided by the environment, due to memory failures or to variations in the motivation which sustains involvement in processing a task, may create variations between the past and the present representation or the attempted solution of a task. For another, variations may be generated because of the structure of the brain itself. For example, cognitive neuroscientists (see Changeux & Connes, 1992/1995) argue that the two hemispheres of the brain, due to their lateralization, may create independent and more or less divergent representations of the same information structure present in the environment. In fact, one may argue here that variation is a basic mechanism for the accurate recording of the environment at the level of perception as well. For instance, binocular and motion parallax, which generate variations in how objects are recorded on the retina and the brain, are responsible for our depth perception and stereoscopic vision (Held, 1985). Finally, variations between minds in the representation of the same state of the world, which is understandable from about the age of four years (Perner, 1991; Wellman, 1990), if not much earlier (Leslie, 1987), may be another cause for variations within minds when they interact with each other about a given state. To conclude, it is proposed here that the very nature of the environment and the mind ensures the instability that is necessary for change to occur in the mindís representations and coping operations for the environment. In line with this view, it is recently becoming increasingly accepted that variation in relative frequency of use of existing strategies is the rule in the development of different domains, such as arithmetic (Siegler, 1994, 1995, 1996) and causal thought about the physical and the social domain (Kuhn, Garcia-Mila, Zohar, & Andersen, 1995).

The second mechanism which is responsible for furnishing criterion representations is associated with the SCSs involved in the environment-oriented level of knowing. These, by construction, function as knowledge extraction mechanisms attuned to specific patterns of information that generate some kind of accurate information about the environment from the beginning of life. That is, the theory assumes that each SCS involves inbuilt structures that abstract specific types of representations from corresponding information structures once a minimal set of conditions are met. These are the kernel elements of each SCS mentioned above. This interpretation of initial meaning-making is consistent with modern infant research which suggests that the fundamentals of categorical (Soja, Carey, & Spelke, 1991), quantitative (Gelman & Gallistel, 1992), causal (Starkey, Spelke, & Gelman, 1990), spatial, (Landau, Spelke, & Gleitman, 1984), and social understanding (Trevarthen, 1977) are present from the very first months of life.

Thus, the kernel elements function as mental yardsticks which may be activated and used for the evaluation of the more complex and / or less accurate products of the functioning of the SCSs at different points in time. These products are generated by the variation-generating mechanism specified above. For instance, a system that somehow always "knows" that numerosity is constant when, say, we have sets with less than four elements or sets whose elements are organized so as to correspond one-to-one, will seek to understand why it does not appear to be constant under certain other conditions, say when an elongation transformation has been applied to one of the sets. Thus, the system is self-corrective because construction always involves a grasp of some aspects of the true state of affairs. Admittedly, this is a rather drastic way to resolve the so called learning paradox, which asks ìhow can one learn something when one knows nothing about it to start with?î The answer offered here is straightforward: One always knows something to start with. Thus, the learning paradox reflects the ignorance of the psychologists to specify the primitives of different thought domains rather than that of the developing person! It needs to be noted that this assumption is consistent with dynamic systems theory which assumes that there can be no development unless there is a minimal level or potential to start with (van Geert, 1994).

In Gibsonian terms (Gibson, 1979), the fundamentals of each SCS is automatically abstracted from the SCS-relevant affordances of the field of the environment concerned. Responding to the affordances guides the system to modify "knowing assumptions" that do not fit. This assumption renders development a process of mutual validation of concepts in which the older and more basic ones, which have a higher level of confidence, help check, compare, select, modify, or reject the newer, frequently more complex ones, which have a lower level of confidence.

It may be noted here that modern attempts to model cognitive change through a parallel distributed connectionist architecture advance equivalent assumptions regarding the spread of change from a fundamental to a more advanced level. In these architecture the initial knowledge-state of the system is defined by the initial strengths (or, weights) of the connections between the hidden units and the other units of the network, in so far as, if the connectionist distributed networks build any kind of representations, these must reside in the connection weights of the hidden units. These connection weights specify how the input is to be interpreted and how the output is to be assembled. One of the learning rules that may be used in training these networks is that of back-propagation. According to it, learning results from the gradual modification of the connection weights, as the system tries to minimize the error in its output, that is the difference between the actual output it produces and the desired output. More specifically, this modification starts from comparisons between the activations of the output units and the target output and it propagates back into the lower levels of the system until the discrepancy between actual and desired output acquires is minimized. Since these weights encode the representations that the system builds, we could say that the systemsí learning results from the modification of the representations throughout the system. We propose that each of our SCSs may be conceived as a multilevel parallel distributed processing edifice in which the change history starts form the kernel elements and goes to the more or less stabilized operational and computational skills and strategies like pragmatic reasoning schemas and the incessantly changing theories and belief systems about the world.

According to our theory, the modification process is not fully or always blind or stimulus driven. That is, it is assumed that in order to be able to check, compare, select, modify, and reject, the mind must be able to record and monitor its own activity, the products of its activity, and somehow be aware of both the monitoring processes as such and their products. It is only under this condition that divergence between two or more alternatives can become known so that errors can be marked and patterns of error-marking activities can be abstracted and stored for future use. In our theory, the recording is the responsibility of the SCSs and the processing system.

Comparisons, error-marking activities, and decision-making is the responsibility of the hypercognitive system. Because of its monitoring, regulation, and selection processes, the hypercognitive system contributes to all three main aspects of development noted above. That is, on the one hand, it generates evaluation or validation criteria that can be used by the thinker in order to avoid mistakes from the beginning, thereby increasing efficiency through sparing of resources. On the other hand, it establishes increasingly powerful interpretation, processing, and action networks that can be called upon in the future, thereby expanding the field of application of the environment oriented SCSs. The mechanisms used to establish these networks as well as the networks themselves will be explicated below.

To summarize, the present model suggests, first, that the products of developmental change at any given moment are never entirely new relative to the already available constructs because they grow from these constructs as adjustments of present "tentative alternatives" to core or prototype concepts that define a structure as it represents "standard affordances" in its own environment. A second claim of the model is that the origins and the main directions of developmental change reside in the structures involved in the architecture of the human mind. That is, the micro-adaptations which result in developmental changes are, on the one hand, constrained by the SCSs because they are effected under the guidance of SCS-specific kernel elements. Thus, the SCSs always remain in place, although they do develop and expand. On the other hand, the way they are stabilized, compiled, and represented is constrained by the systemís processing resources and the hypercognitive capabilities.

Types of Change

The analysis of the origins of change attempted above suggests that there are three different types of change that the developmental psychologist needs to study: (1) changes within individual structures, (2) changes in the relations between structures within a hierarchical level, and (3) changes in the relations between hierarchical levels. Below these different kinds of change will be discussed in some detail. The aim will be to show why each combination of change occurs, how it occurs, and how it can be studied and modelled.

Changes within Structures

Organizational changes within structures refer to changes that affect the relations between the elements that by definition pertain to the same SCSs. They are thus concerned with the same reality domain. For example, in the quantitative SCS, the integration of the representation of numerosity-affecting operations, such as addition or subtraction, with the representation of numerosity-irrelevant operations, such as changes in the spatial distances between the elements of a set, is an example of this kind of change. Changes of this kind may result in an increase in the field of application of the structure, because they enable the person to apply the structure in areas of the structure's domain that were out of reach before the integration. For instance, in the example above, numbers larger than four can be conserved. They also result in a better focusing of the elements involved in the integration. For instance, the integration of the operations mentioned above enables the individual to understand that longer may usually imply more, but this needs to be qualified by other considerations as well.

Changes within Hierarchical Levels

Changes in the relations between different structures within a hierarchical level refer to mapping an element from one structure, say the quantitative, onto an element taken from another structure, say the causal, or the spatial. These kinds of change are very different from the changes within structures discussed above. Their main difference lies in the fact that they are concerned with structures which represent different domains of reality, they involve different computational or operational rules and algorithms, and they may even require different symbol systems to represent their domains and sustain their computational functioning. One may refer here to changes that affect the relations between the quantitative and the spatial or the relations between the quantitative and the causal SCS. For instance, we know that a basic characteristic of the numerical domain is continuity in the succession of number elements. Counting natural numbers can go *ad infinitum* and even the decimal numbers between two integers are infinite. On the other hand, a dominant characteristic of causality is its discontinuous character. That is, the presence-absence of the cause may correspond one-to-one with the presence-absence of the effect. Despite this basic difference, however, we do invoke the world of quantities to understand and specify the causal world. However, there are difficulties in interrelating these domains both at the level of the culture and the level of the individual. Crosbyís (1997) recent work shows the difficulties that natural sciences had to overcome over the centuries in order to use mathematics in their models about the world. This is due to the fact that these changes require special codes that can be used for the interconnection between the different domains. An example of such a code may be the arbitrary symbol systems of physics or chemistry which help translate causal relations between reality elements into quantitative relations and vice-versa. These codes are not readily available and special training is necessary, if the person is to become able to grasp the inter-SCS relations. However, these structural changes, once effected, provide access to aspects of reality or to means for manipulating reality that far exceed the potentialities afforded by changes within a structure.

Changes across Hierarchical Levels

The picture becomes much more complex when we come to changes regarding the relations between cognitive elements which belong to different hierarchical levels. These changes may initiate at any of the three main levels of the mental architecture, that is the processing system, the SCSs, or the hypercognitive system, and generalize to the any of the other two levels in any direction. In general, these changes function as dynamic loops with a specifiable--often arbitrary--origin. That is, the change in the first hierarchical level affected opens the way for changes at the other hierarchical levels. Then these changes at the other levels may loop back and affect the level that originated the chain. Obviously, it is very important for developmental theory and research to specify how these changes occur and how they affect the relations between the hierarchical levels.

A classical example of change of this type is that which affects the relations between the dimensions of the processing system, that is, speed of processing, control of processing, and working memory, on the one hand, and various domain-specific abilities which belong to the SCSs, on the other hand. The idea is that a change in any of the parameters of the more fundamental level of the cognitive architecture opens the way for structural reorganizations at the level of the SCSs or the level of hypercognition. Many scholars have demonstrated the relation between the changes in the various parameters of the processing system and the changes that occur in various conceptual domains (Case, 1985, 1992; Halford, 1993; Kail, 1988; Pascual-Leone, 1970; Demetriou et al., 1993a).

A similar type of transfer across hierarchical levels has been observed in the relations between the hypercognitive system, on the one hand, and the processing system or the environment oriented systems, on the other hand. In fact, the recent proliferation of research on the effects that metacognitive training may have on various conceptual domains, which is very popular among educationally oriented scholars, highlights this type of change transfer across the levels of mental architecture. That is, it indicates that imparting on the student a given metacognitive strategy or skill will beneficially affect the functioning of domain-specific skills or processes. Recently, Kuhn et al (1995), in their microgenetic studies of the development of causal thought in the physical and the social domain, have stressed the importance of metastrategic competence as a factor of the development of problem-relevant strategies. ìMetastrategic competence includes understanding of both the value and the limitations of a strategy--in practical terms, of knowing how, when, and why the strategy should be usedî (p. 109). In fact, Shayer (1992; Adey and Shayer, 1992) showed that training addressed to metastrategic competence does have beneficial effects, which manifest themselves long after training and which last long.

Also, changes in the SCSs frequently may cause changes in the two general systems. For instance, the practice with arithmetic operations provided by school may lead the children to discover their storage limitations. In turn, this may motivate them to develop strategies that would overcome these limitations. On the one hand, these strategies may raise the child's self-monitoring and self-regulation facility. On the other hand, they may eventuate in more efficient handling of processing capacity (see Weinert & Helmke, in press).

In our laboratory we studied how the relations between the two knowing levels of mind change with age. Specifically, in the study which investigated the relations between the SCSs of the environment-oriented level and the various aspects of the self-oriented hypercognitive system, we analyzed the structural organization of these dimensions separately for each of the age groups 11 to 15. It was impressive to find that the same constructs were found for all types of measures (performance, self-awareness about performance, and thinking styles) across all five age groups. In fact, even the factor loading and the coefficients indicating structural relations between factors *within* each of the three sets of scores were by and large the same across age groups. There was, however, a very interesting difference between age groups, which seems to have captured a systematic developmental trend. Specifically, the relation between the higher-order factor, which stands for the environment-oriented level of the mental architecture (and it accounted for the variance of the various domain-specific constructs) and the higher-order factor which stands for the self-oriented or the hypercognitive level (and it accounted for the variance of the self-awareness factors corresponding to the domain-specific constructs and various thinking styles constructs) was practically non existent at the age of 11 years but it increased systematically and became strong at the age of 15 years (i.e., the correlation between these two higher-order factors was .05, .11, .20, .45, and .60 at the age of 11, 12, 13, 14 and 15 years, respectively). This finding indicates that many of the changes traditionally associated with the transition from childhood to adolescence may affect primarily the communication between the two knowing levels of the mental architecture than the modules and the processes themselves which reside at the levels. That is, the monitoring and representation of the environment-oriented level by the self-oriented level becomes increasingly accurate and detailed.

Mechanisms of Change

The discussion about developmental causality has shown that each system can function as a cause of change in the other systems. However, the forms and the magnitude of change is not always the same. The change which originates in any of the general systems must be different in kind from a change that originates in any of the specialized systems. Moreover, the change which transcends the boundaries between different systems may be different in nature from the change which circulates from the one component to the other within the same system. Therefore, one is justified assuming that different types of change take place through different mechanisms. Below we will discuss three types of mechanisms: specifically, we consider mechanisms underlying changes in units which reside (a) in different hierarchical levels of the mental architecture, (b) in different SCSs, and finally (c) within the same SCS.

A number of authors have provided valuable insights into the nature of the mechanisms that are responsible for cognitive developmental change.

Prominent among these authors is Piaget (1985) himself, Flavell (1972), and Fischer (Fischer & Pipp, 1984). The discussion below about mechanisms of change will draw considerably upon the ideas of these scholars. However, it needs to be pointed out that we will attempt to differentiate these ideas so that they can fit with the assumption of a hierarchical and multi-dimensional mental architecture. That is, we will attempt to show that different types of change in the relations between mental entities within and across the levels of mental architecture require different mechanisms to be effected. Thus, to avoid confusion, new terms will be used here to denote the different mechanisms. These terms aim to emphasize the position advanced in this paper that changes affecting different levels of the mental architecture or different structures within a level are effected through different mechanisms and that, therefore, the mental architecture constrains the dynamics of change. We propose five such mechanisms: *bridging, interweaving, fusion, differentiation*, and *refinement*. Table 1 summarizes the main characteristics of these mechanisms.

Bridging. It refers to the construction of a new mental unit by establishing relations between units already available. However, the new unit does not displace or substitute for the units involved in the construction. Thus, this mechanism is particularly apt to describe the establishment of relations between different SCSs, which, although necessary for the solution of complex problems that require the activation of more than one SCS, do not affect the functional autonomy of the SCSs.

The construction of a new mental unit through bridging presupposes that a number of requirements are met. First, there must be a need for the new unit which springs from the fact that already available solutions to a problem are recognized as irrelevant or insufficient. Second, the search for a new solution results in the identification of two or more units as tentatively relevant to the problem and to their recognition as somehow consistent with a kernel element that guides the right-and-wrong-marking process. Third, the processing potentials or (*or* here is meant to be inclusive) the monitoring and regulation strategies available are enough to enable the individual to envision the to-be-bridged units together and work out their possible connections that would result into the new construct. If these three requirements are met, the units involved will somehow (see below) be bridged or inteconnected.

An example of bridging would be the use of graphical representations, which belong to the spatial SCS, to express categorical or covariation relations, which belong to the qualitative or the quantitative SCS, respectively. Another example would be the use of algebraic functions, which belong to the quantitative-relational SCS, to express causal relations, which belongs to the causal SCS. Obviously, interrelating these abilities does not affect the autonomy of any of them nor does it lead to their abolition. However, it broadens the scope of the problems that the person can represent and process.

Research on the use of graphics as a means for enhancing understanding of relations in various domains is relevant. This research shows that building the connections between the target field and graphics is a demanding and cumbersome processes that needs special instruction and effort to be effected (Kirby, 1993). This is fully understandable from the perspective of the present theory. Building the connections necessary between a system of graphics and the target relations requires crossing the SCS boundaries. This implies that kernel elements are not readily available to direct the process. Thus, the new relations have to be constructed through a variation-and-selection process which at points may be misdirected or counterintuitive.

Interweaving. The integration of previously unrelated mental units within an SCS for the sake of the construction of a new mental unit may be effected for the same reasons and, in the same way, as bridging. However, integrating units within SCSs may engender a preference for the use of the new unit and an ensuing reduction in the isolated use of the units involved in the integration, although these units may still be available to the thinker.

Thus, we propose the term *interweaving* to denote the mechanism which blends the units involved intimately and alters their probability of use in favor of the new unit. For example, the interweaving of hypothesis formation with the isolation-of-variables ability within the causal-experimental SCS will result in the model construction ability. Although each of the two specialized integral abilities may always be present in itself, the model construction ability, once established, will dominate the other abilities whenever the individual will have to deal with a problem which requires any of them. We have provided examples of this process in a number of studies (Demetriou et al., 1991; Demetriou et al., 1993b; Demetriou et al., 1996). The functioning of this mechanism is much less demanding than bridging because common kernel elements or schemes within the SCS concerned facilitate the establishment of the connections required (Demetriou et al., 1993a, Study 2).

Insert Table 1 about here

Fusion. The construction of new mental units on the basis of already available units within an SCS frequently results in the disappearance of the units involved in the construction. An example here would be the integration of the concept of number succession with verbal counting. Once this construction is established, it is improbable that thoughts about number succession can be effected without activation of the number name sequence or that stating this sequence can be free from a representation of the succession of numbers. We propose the term *fusion* to refer to the mechanism which generates new mental units within SCSs which absorb their building blocks thereby causing their extinction.

Differentiation. All of the mechanisms discussed above are concerned with the construction of a new mental unit on the basis of other, already available units, either within the same or across different SCSs. However, development is frequently tantamount to an improvement in the accuracy of the functioning of an already available mental unit. This usually implies either a better focusing of the unit on those target elements (environmental or mental) or a better mapping of the possible variations of the unit onto the target elements to which is variation is related. The mechanism which is responsible to bring these changes about is *differentiation*. An example of differentiation may be the understanding that number names cannot be used in the same way to denote increase in natural numbers and in fractions. The reason is that increase in the former corresponds one-to-one to the sequence of number names whereas fraction names are more complex compositions. For instance, provided that the nominator is the same, larger numbers in the denominator imply a smaller value for the fraction. Hartnett and Gelman (in press) showed that it takes time and effort to differentiate between the many variations of counting or measurement.

Refinement and elimination. A mechanism similar to differentiation is *refinement*. This mechanism is responsible for the abandonment of strategies or skills involved in a mental unit when they are found irrelevant or redundant to the unitís field of application. Thus, refinement involves *elimination*. Such a mechanism is particularly useful at the beginning of the acquisition of a new strategy when the tendency to continue to apply the old strategies is still very strong. This mechanism is needed to ensure that the individual will avoid applying the old concepts or strategies instead of the new ones when she will have to deal with relevant problems. A classical example of elimination is the rejection of quantity judgments on the basis of spatial criteria once the quantity-relevant structure is established. The increasing schematization of operations in all mental organizations, which is a basic characteristic of both grand scale cognitive development and the acquisition of expertise (Chi, Glaser, & Rees, 1982), may to large extent be ascribed to refinement. That is, the more purified the operations become of irrelevant elements the more smoothly and efficiently they can be applied on their target elements and the more their possible interrelations can be envisioned and worked out.

The functioning of all five mechanisms described above depends on a kernel element in some way. Specifically, if two mental units are to be bridged, interweaved, or fused, they need to be consistent with each other. In turn, to be found consistent, they must reproduce to a minimum degree the defining characteristics of a kernel. For instance, the graphical representation of a relation of two variables requires bridging the understanding of number sequences with the understanding of spatial succession. However, underlying both of these two understandings is a more fundamental understanding: namely that something is common in both cases, ordinalities in the first case and succession of points in space in the second case. Likewise, the variants that come out of the differentiation of a more global mental unit need to be found consistent with each other in some respects and inconsistent in some other respects. This can only be effected through their mapping onto a more prototypical construct. Finally, the elimination of mental components in the process of refinement presupposes that the components to be eliminated are envisioned together with the kernel and recognized as inconsistent with it.

Developmental Hypermechanisms: Ideotransmitters and Ideostabilizers

The mechanisms discussed above may describe how new cognitive units are engineered on the basis of older units at the various levels of the mental architecture. That is, these mechanisms are involved in the production of new mental units by elaborating or extending the same mental unit (differentiation or refinement) or by building connections between mental units which belong to different sub-systems within the same (interweaving or fusion) or different SCSs (bridging). However, these mechanisms do not explain two important aspects of the mental construction process. That is, first, they do not explain how the different units involved in each of these mechanisms are compared with each other and with the criterion representations mentioned above. For example, how do the persons build for themselves the correspondences between (i) the covariation of two number sequences that stand for variables A and B, (ii) the causal relation between these variables, and (iii) the space defined by two intersecting lines of a conventional figure so as to understand that, under certain conditions, covariation can indicate causality and that both can be illustrated graphically? Second, the five mechanisms discussed above also do not explain how the new mental units, once created, get stabilized, identified, and stored so that they can be preserved, recognized, and recalled in the future, whenever the need for them arises. Therefore, the considerations above call for a kind of hypermechanisms that would be able to explain how the five specialized mechanisms do their job and ensure the preservation of their products. We shall attempt to sketch these hypermechanisms in the present section.

Metarepresentation, Analogical Reasoning, and Schematization

Metarepresentation is one of the two hypermechanisms of cognitive change. Simply defined, metarepresentation is a process which looks for, codifies, and typifies similarities between representations to enhance understanding and problem-solving efficiency. In other words, metarepresentation is analogical reasoning applied on representations as such rather than on their content. For example, when a child realizes that the sequencing of the *if ... then* connectives in language is associated with situations in which the event or thing preceded by *if* always comes first and that it produces the event or thing introduced by *then*, this child is actually formulating an inference schema that leads to predictions and interpretations specific to this schema. When abstracted over many different occasions, and somehow tagged (or symbolized) in the mind it becomes the frame which guides reasoning by implication.

Thus, according to our theory, reasoning develops as a result of the interactions between the environment-oriented SCSs and the hypercognitive system. The reader is reminded that the hypercognitive system involves models and maps about intelligence, cognition, and the self, which are used by the thinker to guide on-line process selection, application, adaptation, and evaluation. That is, these models and maps direct the functioning of on-line processing, which intervenes in the functioning of the SCSs. In turn, the interactions between on-line processing and the SCS running at a given period of time feed back onto the long-term hypercognitive models, causing their update and refinement. In other words, as the effects of the monitoring-regulation process are carried over from the one level of cognitive organization to the other, they are "formalized" as systems of action schemes or criteria that become available for future use. Therefore, the hypercognitive system is the locus where representations about past problem-solving performance (i.e., meta-representations) reside as criteria for logical validity and necessity that can be used by the thinkers in order to direct and evaluate their present logical performance.

These assumptions lead to a specific prediction about the development of reasoning. That is, that major changes in the kind of reasoning tasks that can be solved must be preceded by changes in the awareness of the inferential processes involved. Moshmanís (1990) model of the development of deductive reasoning is in full agreement with this prediction. According to this model, deductive reasoning develops in a sequence of four levels. At the first level (preschool age) reasoning schemata are implicitly applied but children are explicitly aware only of the content of thought. In the second stage (primary school age) children are explicitly aware of the inferential process but not of logic as such. Thus, they grasp logical necessity and its violations but they still cannot reason on the basis of logical validity independently of the factual reference of an argument. In the third stage (adolescence) logic itself becomes an explicit object of thought. That is, adolescents are explicitly aware of the form of propositions and arguments so that they differentiate between factual and inferential validity. However, it is only at the fourth stage (adulthood) that they become able to reason about reasoning itself and formalize their conceptions. According to Moshman (1994), the driving mechanism behind this development is *metareasoning,* which involves (i) knowledge about logic, reasoning, and rationality, (ii) control of oneís inferential processes, and (iii) developmental reconstruction of oneís reasoning. Clearly, Moshmanís metareasoning is part of metarepresentation as defined by our theory. In other words, this theory assumes that metarepresentation, which is inductive reasoning applied to cognitive experiences, is the mechanism underlying the development of deductive reasoning because it leads from automated inference to explicit logic and metalogic.

It was argued above that the basis of metarepresentation is analogical reasoning. Thus, if the model is to be valid, these forms of inference need to be present from the beginning. Infant research suggests that this is the case. Research with young infants has shown that they can make judgments based on perceptual similarity very early in life, if not at birth (DeLoache, Miller, & Pierroutsakos, (1998). With regard to analogical reasoning, Wagner, Winner, Cicchetti, & Gardner (1981) showed that infants as young as 9 months of age preferred to look at an arrow pointing up when hearing an assenting tone and at an arrow pointing down when hearing a descending tone. Based on this and other similar evidence Goswami (1992) argued ìthat the ability to recognize relational similarity may not develop at allî (p. 13) because it ìcould be an inherent quality of human reasoningî (p. 15).

Looking for relational similarity underlies all of the mechanisms of change described above, that is bridging, interweaving, fusion, differentiation, and refinement. One may justifiably ask here why one would need to invoke different mechanisms and not reduce them all to their common underlying mechanism. The answer to this question is rather simple from the perspective of our theory. Specifically, the fundamental premise of the theory that there are different cognitive structures which are domain-specific and computationally-specific compels the assumption that relational similarities that may be constructed by analogical reasoning need to be marked as to their status relative to the mental architecture. That is, as to whether they belong to the same or to a different SCS. This is necessary for two reasons. On the one hand, marking the analogies in this regard ensures that the thinker knows how close to reality the analogy is. For instance, within-SCS analogies may lead to fusion and to the eventual elimination of the base schemes involved in the analogy because these schemes are alternative representations of the same type of relations. However, the base schemes involved in cross-SCS analogies represent relations which are different by definition. These differences need to be preserved even after an analogy is established, because their elimination may endanger the adaptability of the system. For example, it may be useful, for purposes of exemplification, to represent the flow of electricity through the wires by analogy to the flow of liquid through tubes but it would be very dangerous if you seek direct contact with electricity as you may do with some liquids, such as water.

Of course it is recognized that there are two additional factors which are effective in the process of building new mental units out of units already available. Specifically, the knowledge available does influence the units that can be constructed because it provides the raw material on which the similization processes will be applied (Goswami, 1992). Moreover, the complexity of the units that can be constructed is also constrained by the potentialities of the processing system. Halford (1993) has shown that the structure-mapping processes which underlie analogical reasoning do depend on working memory capacity. An implication of the dependence of structure-mapping processes on prior knowledge and processing resources is that the various specific change mechanisms presented above may not be equally possible at different points in development. We will elaborate on this possibility below.

Symbolic Individuation

It has been pointed out above that constructing new mental units is not tantamount to having them available for future use because they may fade way unless particular measures are taken for their preservation. We propose that one of the reasons why new mental units are lost is their failure to be connected to a symbol which will make them identifiable and mentally manipulable. Therefore, the endurance of new mental units depends on a process of *symbolic individuation*. This is a process which pairs newly generated ideas with specific symbols (Demetriou, 1993). These symbols, which may be idiosyncratic, like mental images or personal scripts, or conventional, like language or scientific formalisms, may be regarded as comparable to the process of *identity ascription* to a newly born individual. Giving a name to a newborn reduces the possibility that this individual will be mistaken for somebody else. This information also ensures that this individual will be integrated into the family tree of his parents and his relatives.

It needs to be noted here that symbolic individuation is related to metarepresentation at least as much as analogical reasoning. In a sense, analogical reasoning and the mechanisms associated to it may be conceived as a kind of *ideotransmitters* that carry meaning from one representation to the other and in doing so they generate new mental units. Symbolic individuation is complementary to these other mechanisms in that it functions as a kind of *ideostabilizer*. That is, it encapsulates the new units into symbols which have or are given meaning of their own so that they can be used in the future and communicated to others.

There is evidence to indicate that acquiring and stabilizing ideas requires the concomitant acquisition of special symbolic codes. Our studies of mathematical thought development indicated that manipulating algebraic symbols is necessary for the construction of complex mathematical concepts (Demetriou et al., 1991, 1996). In line with this evidence, Nesher and Sukenik (1991) have shown, by means of a training experiment, that the learning of mathematical relations (i.e., ratios and proportions) is most enhanced when the training experiences provided in the experiment were paired with relevant formal representations. These representations enabled the subjects to summarize and manipulate their training experiences. Thus, future research would have to illuminate the nature of symbolic individuation in the different phases of development, identify the causes of its development, and explain how they occur.

The process of individuating newly constructed mental units through their association with a symbol may vary considerably as to *originality* (e.g., a new idea may be defined in reference to an already available word or it could be defined in reference to a new word or symbol), *completeness* (i.e., the degree to which the symbol used is able to express the various dimensions of the idea), and its *communicability* (i.e., the degree to which the new idea can be communicated to other individuals) is concerned. Our knowledge of these three dimensions of symbolic individuation as a mechanism of cognitive development is practically non-existent.

Although a mechanism of cognitive development, it is highly probable that symbolic individuation itself does change with age and experience in regard to all three dimensions noted above, that is in regard to originality, completeness, and communicability. This is plausible because the construction of new mental units through the mechanisms discussed above in conjunction with symbolic individuation provides the raw material for new bridging, new interweaving, or new fusions which expand the field and the flexibility of the symbolization process which, once exercised will engender new units, which will engender new symbolization needs and skills and so forth. The studies by de Loache and colleagues (DeLoache, Uttal, & Pieroutsakos, 1998) are in line with this assumption. In a series of experiments they showed that pre-school children have difficulties in understanding the relations between a referent (a room) and a symbol (the same room at another scale), even if the referent and the symbol are identical in all respects but their scale. According to de Loache, the understanding of the relations between a symbol and its referent develop as a function of many parameters, such as the novelty or the complexity of the symbol and the referent.

Second, it is also plausible to assume that symbolic individuation occurs differently in each of the various SCSs. This assumption is made all the more reasonable by the fact that the SCSs are biased towards different symbol systems. At the extreme, one may contrast here the imaginal and pictorial symbolism of the spatial-imaginal SCS to the arbitrary mathematical symbolism of the quantitative SCS. Invoking or shaping a mental image to individuate a newly conceived figurative idea cannot be the same as invoking or shaping mathematical symbols with the aim to individuate a newly conceived quantitative idea.

The results presented by Tolchinsky-Landsmann (1993) are highly informative in this regard. She asked 4-, 5-, and 6-year old children to use written symbols to denote the identity (*what* objects are there on a card) and the quantity of concrete objects (*how many*). The results showed clearly, in line with the assumptions put forward above, that from the age of four years children understand that different symbol systems, which obey different constraints, are needed to denote the identity and the quantity of things. Specifically, they produced interlinked, handwriting-like strings of symbols to denote identity and separate, repeated symbols to denote quantity. From the age of 5 children used letters to stand for identity and ciphers to stand for quantity. In a similar vein, Strauss and Schneider (1993) showed that there are no relations between childrenís understanding of ratio comparisons and their ability to represent these relations graphically. In line with this results, research in our laboratory has recently shown that from about 5 years of age children use different codes to represent graphically categorical, causal, and spatial relations (Bonoti, 1998).

The General Character of Development

According to the above analysis, development is possible because a person's mind is multisystemic and multistructural. At the level of the person, a change in any component of mind triggers a whole set of changes aimed at re-instituting the functional tuning between the component that has changed and those related to it. In this process, the system makes use of kernel elements or schemes that can ensure that the construction process will preserve the dynamic structure of each of the SCSs. Thus, any change is regarded as a potential radiator of growth pressures on its neighboring components within the system. The eventual result is of course a function of several crucial factors.

At the level of the individual, the nature of change depends upon the specific system that initiates a chain of changes and the condition of the other systems at the given period of time. This last factor is important because it determines the readiness of the other systems to move from their present state and follow the changing system. For instance, it was argued previously that developmental theorists agree that a change in the general processing system raises the general potential of the organism to assemble general strategies and grasp the relations between SCS-specific units which would be impossible at the previous functional level of the processing system. Nevertheless, this potential is not always realized. Our analysis of individual change patterns of the subjects tested on a number of tasks addressed to the various dimensions of the processing system and several SCSs showed that a change in the speed or control of processing or in working memory does not always result in changes in the SCSs (Demetriou et al., 1993a, Study 4; Demetriou et al., submitted-b).

This evidence is congruent with the assumption that the massive changes that have been associated by developmental theory with major shifts in development are possible when the changes in one of the systems accumulate up to a certain level, and then a change in another system occurs that functions as a catalyst to trigger the reorganization of mind as at a new representational or structural level (Demetriou et al., 1993a). The changes occurring at crucial developmental turning points, such as those leading from sensori-motor to representational intelligence at about the age of two years or from concrete to abstract representations at about the age of 12 years, seem to be of this variety. For instance, there is evidence that speed and control of processing change rapidly between 9 and 11 years. These changes provide the necessary processing capabilities that can be catalyzed by improvements in self-monitoring and self-regulation, which occur at about the age of 11-12 years, and make the pre-adolescents able to take a hypothetical, what-if, stance about themselves and reality and to accept that they must work with models of reality rather than with face-value representations of reality. This new stance opens the way for the changes observed in the various SCSs throughout adolescence (Demetriou et al., 1993a, Studies 4 and 5).

Once a major change has occurred, each of the various systems tends to draw upon itself as it develops. A consistent finding of our own is that at the beginning of major developmental changes, SCS-specific changes depend on the condition of the general systems and even receive influences from other SCSs. After a certain point, however, when a given sequence of changes takes off, its subsequent levels depend much more on its preceding levels than on the preceding levels of another SCS (Demetriou et al., 1993a, Study 1). This pattern brings the discussion to another important issue. Specifically, why do interactively generated changes in the different systems of mind gradually tend to become autonomous and self-sustained?

Three complementary reasons seem responsible for this phenomenon. First, even when activated from outside, the rate and forms of change in a system will be largely dependent on the state and the peculiarities of each of the components involved in that system as well as on that systemís organisation as such. For instance, how fast a change can propagate in a system depends on the penetrability of each component to influences coming from neighboring components but also from the amenability of the between-components relations as such to move from the present dynamics into a new one. In turn, these inertial constraints of a system depend upon earlier habitual patterns associated with the systemís functioning. This point leads to the second reason. Specifically, however it has been initiated, the change of a system will be effected in interaction with the domain of the environment the system is affiliated to. Therefore, the peculiarities of each systemís domain together with the opportunities the person has to interact with this domain at the times which are critical for the change to survive and spread is very important. Finally, the consolidation and propagation of change within a system depends upon the relations between this system and the two general systems.

That is, on the one hand, it depends upon the way in which the components make use of the processing resources available at the given phase. It was found, for example, that the SCSs, are differentially related to the processing system. For instance, the quantitative-relational SCS is more closely related to the condition of the processing system than the spatial or even the causal SCS (Demetriou et al., submitted-b; Platsidou, 1993; Zhang, 1995). Thus, different SCSs make use of a change in the processing system in a different way. As a result, their development that may result from this change in the processing system is also different.

On the other hand, it depends on the relations between the various SCSs and the hypercognitive system. For instance, we found that some SCSs, such as the quantitative-relational and the spatial-imaginal, are more visible to the hypercognitive system than others, such as the verbal-propositional and the causal-experimental. This implies that at crucial points in development different systems may differentially affect the functioning of the hypercognitive system and this may differentially intervene in the further development of the SCSs (Demetriou et al., submitted-b).

The discussion above about possible differences in the relations between the SCSs as such as well as between the SCSs and the two general systems at different points in a developmental cycle does have an interesting implication regarding the mechanisms of change discussed above. That is, it implies that different mechanisms may dominate at different points within a developmental cycle. For instance, it seems reasonable to assume that at the beginning of a cycle the functioning of the SCSs as such needs to be raised at the level of the new potentials afforded by a catalytic change before they can be interconnected with each other. Therefore, at the beginning of a cycle, differentiation and refinement may be more necessary than other mechanisms as a means for raising the concepts, strategies, and skills within SCSs to the level of the new potentials. Later, however, when the SCSs are raised to a satisfactory level of functioning, inteweavings and fusions may become possible or necessary as a means for establishing new connections between whatever has already been achieved within the SCSs. At the end of a cycle, connections that bridge concepts and skills from different SCSs may be possible.

Is then development continuous or discontinuous? It is both. If viewed from the point of view of its end-products, development is discontinuous. That is, a major representational shift such as those mentioned above may be seen as a cutting point which demarcates the end of one developmental cycle and the beginning of another. The age phases coinciding with these changes are usually regarded as phases during which there is an acceleration of development. This acceleration is regarded as an indication of the fact that the cognitive system is raised to a new level of functioning or that the possibilities of this level enable the individual to quickly acquire new abilities in various domains. Thus, discontinuity has a double meaning: it refers (i) to changes in the rate of change and (ii) to transformation in the kind of mental process that the cognitive system can execute and the kind of concepts that it can construct.

However, if viewed from the point of view of the dynamics underlying structural changes, development appears to be continuous rather than discontinuous. This is so because of the very nature of the mind itself. Being both an open and self-regulated system, it is always in a state of micro-adaptations. Thus, to the extent our measures are refined enough to spot these micro-adaptations between different blocks of mental units, development would be shown to be a continuous process. This is for two reasons. First, in regard to within-structure changes, Kuhn et al (1995) and Siegler (1995, 1996) were able to show, by using a microgenetic method, that within a given time window there is always a kind of cognitive fermentation. That is, at any time, some ways of thinking are prevalent at the beginning and then decrease in frequency; others are very weak and infrequent at the beginning but they gradually increase in frequency until they dominate; others remain weak and infrequent although always present, and still others fluctuate between being frequent and infrequent throughout the time window. Second, it is equally difficult to decide where to draw the cutting line between different developmental levels even when these developmental levels appear qualitatively different. We saw that in these cases the acquisition of the characteristics of the higher developmental level are prepared by changes in the characteristics of functions or processes which reside at a lower level. A pertinent example here is the change in the dimensions of the processing system from 9 to 11 as a precursor to the changes in the level of functioning of the various SCSs from 11 to 13 years of age. Therefore, discontinuity in development is a phenomenological concept which has some meaning only if examined in reference to how an observer--or even the developing person herself--sees the products of development once it has occurred. It does not describe 'hot development" as it occurs.

Relationships with Other Theories

The theory advanced here is similar to other theories in some respects and different in others. Due to space limitations, a comparison we will be attempted with three types of theories. That is, the theory will first be compared with the so called neo-Piagetian and post-Piagetian theories of cognitive development because they all originated from the same tradition. Then the theory will be compared with modern connectionist models of development because these models, although coming from a very different tradition, show some promise in modeling and explaining change, which is the focus of the present article. Finally, the theory will be compared with theorizing and research in developmental cognitive neuroscience, because cognitive developmental theories need to be evaluated for consistency with evidence about the neurological substrate of cognitive architecture and development.

Relationships With Neo-Piagetian and Post-Piagetian Theories

The theory is similar to the neo-Piagetian theories in two respects. First, it shares with them the two of the three levels of the mental architecture described here. That is, that there is a lower-level capacity system and an environmental-oriented level of knowing, which involves problem solving skills and that changes in the lower-level system cause (Pascual-Leone, 1970) or constrain (Case, 1985; Halford, 1993; Kail, 1988) changes in the other level. However, the present theory differs from these neo-Piagetian theories in the following four respects.

First, the present theory analyzed the processing system in terms of three dimensions (i.e., speed and control of processing and working memory). All other theories focused on one of these dimensions, usually working memory, and only occasionally dealt with any of the others, speed of processing in particular. In fact, the theoryís position in this regard is close to classical psychometric theories of intelligence which assume that mental speed and efficiency define general intelligence which underlies performance on very different tasks and domains (Jensen, 1982; Spearman, 1927).

Second, this theory delineates a number of domains which reside on the environment-oriented level of knowing and which are considered to be as primary as the processing system. These domains are defined in reference to the types of relations in the environment that they represent and process. In fact, the theory is closer to the neo-nativist tradition in this regard than to the Piagetian tradition. It may be noted that Case (1992; Case, Okamoto, Griffin, McKeough, Bleiker, Henderson, & Stephenson, 1996) has recently adopted the idea that different domains or, in his terms, ìcentral conceptual structuresî may be part of the machinery of the mind from the beginning. Interestingly, most of the domains he identified coincide with the domains proposed here.

Granted, other researchers point to different types of domains. Specifically, research on the understanding of different phenomenological aspects of the world has identified three domains: the biological, the physical, and the psychological (Karmiloff-Smith, 1992). These domains are supposed to be differentiated on the basis of ontological rather than relational and computational characteristics. That is, they reflect the fact that entities involved in each of these domains differ from those involved in the others in important respects, such as their appearance and behavior.

These two types of domains are not incompatible. In fact, it seems plausible that the relations which characterize relationally differentiated domains run across the ontological domains. That is, all types of relations can be found in each of the three ontologically distinct domains mentioned above. For instance, there are categorical, quantitative, causal, or spatial relations in the biological, the physical, and the psychological worlds, although these relations are not entirely the same in the three domains. For instance, biological causality (such as the genetic transmission of characteristics) involves peculiarities that are not present either in physical or psychological causality (it is constrained by species membership, it requires mating, etc.). Physical causality requires the transmission of energy. Psychological causality may take place in fractions of a second, and it does not require any energy or the intervention of any medium. Imagine mood variations caused by the memory of an unpleasant encounter. Thus, it may be the case that each of the ontologically based domains involves a set of defining characteristics which function as markers of the relationships that define the relationally based domains. These markers enable the thinker to grasp a given type of relationship as an example of a particular ontological domain. Future research will decipher how the two types of domains are related and how their relationships change with development. That is, future research will have to highlight how the mechanisms of change discussed in this article intelink the relationally defined domains mapped by our research and the ontologically defined domains mapped by the research of other scholars. For instance, it may be assumed that differentiation enables the thinker to grasp how the same type of relation, such as a causal or a quantitative relation, is applied in each of the ontological domains. Fusion may be used to generalize a given type of relation across different domains. Bridging and interweaving may underlie the construction of complex or overarching concepts that integrate different types of relations within the same ontological domain.

The third difference between this and the other neo-Piagetian theories may be more notable than the other two. Specifically, these theories failed to explicitly recognize self-awareness and self-regulation as an integral part of the architecture of mind. Admittedly, all of these theories speak about some kind of control structures that guide problem-solving. However, probably for epistemological reasons, these theories failed to elaborate on how these structures are involved in meaning-making, decision making, and problem-solving. As a result, these theories do not specify how self-awareness and self-regulation interact with the other levels of the mental architecture to moderate cognitive development.

Some theorists have indeed provided illuminating evidence and insights about the self-oriented level of the mental architecture. Pernerís (1991) and Wellmanís (1990) models for the development of the theory of mind, Karmiloff-Smithís (1992) model of representational redescription, Campbell and Bickhardís (1986) model of knowing levels, Moshmanís (1990, 1994) model of metareasoning, and Kuhn et alís (1995) model of metastrategic development are exemplary in this regard. However, these models do not elaborate on the organization and functioning of the other two levels of the mental architecture, that is the processing system and the environment-oriented systems. We argued here, however, that none of the three levels can be satisfactorily understood without a satisfactory understanding of the others. In fact, we have attempted to show that development itself is shaped as a result of the interactions between the systems and levels of mind. Admittedly, we still need a long way to go before we understand how the different systems within and across the hierarchical levels of mind communicate with each other in order to enhance understanding and problem-solving skills by building new concepts and skills. We propose that a first step in this direction is to decode how the different mechanisms of change we described are put into action.

Finally, it is indeed the case that all of these theories speak about a number of different mechanisms of change. For example, Case (1985) emphasizes schematic search, schematic evaluation, and schematic retagging. These are activated in the context of general processes such as problem solving, exploration, and mutual regulation of mental schemes to produce new mental structures. Fischer (Fischer & Pipp, 1984) speaks about meachanisms such as intercoordination, which is similar to our bridging, compounding, which is similar to our interweaving, and focusing, which is similar to our differentiation. However, these mechanisms are thought to function across the board. Here we attempted to demostrate that different types of change require different mechanisms and to show what mechanisms underlie each of several types of change.

Feldman and Fowler (1997a) have recently proposed a theory of cognitive change which shares a fundamental assumption with the present theory. That is, that different kinds of cognitive structures require different mechanisms of change in order to develop. This is fully consistent with the present theory. However, Feldman and Fowler define domains along a universal to unique continuum and so they speak about universal, pancultural, cultural, discipline based, idiosynctratic, and unique structures. This definition of cognitive structures is of course very different from, although not necessarily incompatible with, our definition, which is based on relational criteria. As a result, the mechanisms of change proposed by Feldman and Fowler (1997a) are different from our mechanisms. Feldman and Fowler (1997b) and Demetriou (1997) discuss how these different mechanisms may be interrelated.

Relationships With Connectionism

We will discuss the relations between our theory and connectionism from two different points of view. Specifically, we will first focus on the mechanisms of change described above and try to show how these mechanisms can be stated in connectionist terms and modelled accordingly. We will then embark on the issue of the nature of development with the aim to show that our description of development as being both continuous and discontinuous is congruent with the main assumptions of connectionist theory about the nature of cognitive change and learning.

Connectionism and the mechanisms of change. At this point a distinction must be drawn between the *mechanisms of change* and the *content of change*, a distinction which reflects that between *representational mechanisms* and *representational content*. The former is the cause and the latter the outcome. In connectionism the computational mechanism is one and the same in all domains, it is a domain general mechanism. This mechanism is based on brain-style computation, that is in the spreading of the activation of each unit to other units. This results in the transmission, through excitatory or inhibitory connections, of a signal from the input to the output, through the hidden units.

In other words, every aspect of mental activity may be characterized by a set of fundamental computational principles. That does not mean, however, that all cognitive faculties can be *reduced* to the function of this domain-general mechanism. Fodorís (1983) message has been received loud and clear. All it means is that there may be a fundamental computational principle, the one used by connectionist networks, and the various aspects of mental activity (the *SCS*, for instance) are the products of the different organization found in the domain-specific mechanisms that implement these activities, which, nevertheless, are built up out of the same computational principles.

This way the same general computational mechanism can lead, through differential organization, to the various domain-specific functions of the mind, that is to representational differentiation. That is why the distinction between mechanism and content is important. Research in connectionism and neuroscience lends ample support to the above claim. We shall not pursue the issue here ófor an extended discussion see Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996; Johnson, 1997ó except to mention that there is abundant evidence that differences in network, and / or neuronal structure, as well as differences in the initial starting weights, the initial biases, in interaction with various chronotropic maturational factors ófactors such as these could be Thatcherís (1994) cycles of cortical reorganization, the extent and timing of the loss connections and neurons (Johnson and Karmiloff-Smith, 1992) and the environmental input may be responsible for the parcellation and lateralization in the brain, and thus, for the appearance of the domain-specific neural circuits, or modules, and thus, domain-specific representations.

A word of caution is needed at this juncture. We have spoken of a domain-general computational principle that underlies all cognitive phenomena. This does not mean that all domain-specific modules compute information the same way. To see that we must draw a distinction between the general computational mechanism, according to which excitation or inhibition is passed among simple processing units with various levels of activity, and the specific ways that the signal is passed from unit to unit. In connectionist theory there are various activation rules, that is, various algorithms that compute the activation and output of each single unit. Some of them are linear, the output of a unit is a linear function of its input, and some of them are non-linear, the output is a non-linear function of its input. These two ways of processing lead to tremendous differences in the behavior of the network. It is thus probable that at least some of the various mental modules use different, domain specific computations in the sense that we just discussed. In these sense, these modules employ not only domain-specific representations, but also domain-specific computations. Mareschal et al., (1995) constructed a network that was trained to perform visual tracking of objects and search responses. This network contained two separated informationally encapsulated modules, one coding information regarding the location of the object (the *where system*) and the other information regarding the identity of the object (the *what system*).

Now, Jacobs, Jordan and Barto (1991) have shown that if a network is composed of units with linear activation functions and another one of units with non-linear activation functions, then the former will automatically learn to carry out the where task and the latter the what task, since the structure of space is linear. This shows how different computations may lead to specification of function and representation. It also shows that the problem itself, given its computational requirements, constrains the way it can be solved and the systems that can solve it. Thus, given the nature of the task and the computational characteristics of the processing system, it is the match between these two which determines which system will attack which problem. In that sense, the task assignment is innately determined, since the intrinsic capabilities of the system select those tasks to which they are better suited.

By the same token, there is only one mechanism of change in connectionism, the modification of the connection weights and the addition of units and or connections, or the pruning of existing connections. The former belong (Elman et. al., 1996) to the progressive (or additive, or constructive) events and the latter to the regressive (or destructive) events. In connectionist networks, more specifically, an individualís state of knowledge is determined by the weights of the hidden units of the system. Cognitive representational change is regarded as the individualís actual path through the space of possible synaptic configurations, that is, as the transformations of the weight vector in the *n*-dimensional weight space, where ë*n*í is the umber of hidden units in the neural network.

This transformation takes place as a result of the systemís effort to adapt to a new environment, by modifying its connection weights, so that it responds properly to new input-patterns, by ësuperimposingí new representations to those already existing. Thus, the system modifies the ìknowing assumptionsî that do not fit the new environment. In networks that do not have a fixed architecture, learning may also be the result of a change in structure, either by recruiting units (cascade correlation networks), or by pruning connections (meiosis networks).

The above description of the domain-general mechanism of change cannot but be related with our discussion of *metarepresentation*, as one of the two hypermechanisms of change. As we have said, the main function of this hypermechanism, is to look for, codify, and typify similarities between representations. Connectionist networksí main function is to do exactly this same thing. They detect similarities of first or higher order in the input signal and these similarities drive the partition of the activation space of the hidden units. Thus, the general computational principle that drives connectionist networks and is responsible for the building of a similarity metric between the input signals (Clark, 1991; 1993) may be associated with *metarepresentation*.

The extent of the induced changes in the connection weights, that is, learning, depends heavily on the existing values of the connection weights. Since the latter constitutes the knowledge state of the system, one immediately notes that the existing representations have a decisive role in the formation of the new ones. This fits nice with our claim in the discussion of *metarepresentation*, that the available knowledge influences the units that can be constructed because it provides the raw material on which the similization process will be applied. One should bear in mind, at this point, that superimposed representations (that is, the ability of the system to store different representations over the same network of units and connections), which constitute the trademark of connectionist systems, require that no available useful information be lost during the reconfiguration of the connection weights, meaning that the reconfigured system should keep responding successfully to old input-patterns.

Again, this domain-general mechanism of change cannot account for all aspects of change. To do that one must take into account various domain-specific restrictions, that, naturally, differ from one domain to another. Different problems may require different architecture, different coding schemes, different biases, different starting point in the connections-weight space. It is only through the interaction of the domain-general mechanism with the appropriate in each case domain-specific requirements and restrictions that a full account of cognitive representational change can be drawn. As we have said, the structure-mapping processes that characterise metarepresentation depend on the processing resources of the specific domains.

We have proposed the existence of five types of change, namely *bridging*, *interweaving*, *fusion*, *differentiation*, and *refinement* and *elimination*. These types give rise to new mental units, i.e., mental operations, which, applied to the world, generate new concepts. From a connectionist perspective these five kinds of change can be viewed as transformations of the partition of the activation space of the hidden units of a brain-like network, as it learns to adapt to a new environment, by modifying its connection weights. In what follows we discuss the three first types of change, but this discussion can be easily extended to take up all five types of change.

Bridging, is the type of change in the behavior of a network that emerges when the activation space is repartionned, as a result of learning, in such a way that a new area is formed, in which the activation vector lies each time the network faces problems the solutions of which can be found only if the network combines previously independent operations. The newly created activation space, however, still contains the areas that correspond to the combined operations. The new mental unit is superimposed on those that have been combined to generate it. This means that the network can still use the corresponding ëconceptsí, should the occasion arise.

Interweaving, is basically the same type of repartition of the activation space, except that this time the new area takes up space from, and thereby reduces, the activation space of the constituent units. This diminishes the probability that the network will reach equilibrium when its activation vector lies in the reduced areas of its partition space. *Bringing* and *interweaving* may be the results of the strengthening of representations during ontogeny, as a result of experience. This strengthening is related with an increase in connection weight, which is a typical means for learning in connectionist networks.

In *fusion*, the activation space that corresponds to the new mental unit replaces the activation space of the constituent units. This means that the former operational skills become extinct. At an implementational level, this type of change may correspond to the pruning of the connections and/or units of the network. This may be caused by the fact that some units are not activated and are not used by the network that rejects them. Or, it may be the result of the selectionist process of synapses elimination (Changeux, Courrege, Danchin, 1973; Ebbesson, 1980; 1988; Gazzaniga 1983; Changeux, 1985; Edelman, 1987), which is one of the mechanisms for effecting representational change in the real brain, as a response to environmental input and the available organismic resources.

Connectionism and the general character of development. In the section about the general character of development the argument was put forward that development may be either continuous or discontinuous depending upon the level of analysis at which it is examined. In fact, connectionist theory also espouses the view that development may be continuous at one level of analysis and discontinuous at another. According to connectionism, systems learn through certain algorithms and all ìrepresentationsî are built in the connection weights. Learning, and thus change, in connectionism consists in small changes of the connection weights, which, being quantitative, are continuous. These changes, however, give rise to behavior which is discontinuous (new competencies, new concepts). So, in the computational (or behavioral) level development is discontinuous. At the dynamical level, the level which consists in the description of how we learn, since learning consists essentially in small changes of connection weights through training, development is continuous.

More specifically, in PDP, conceptual change is thus viewed as the series of transformations of the weight vector in the weight space, as weights change during the systemís learning. But, as all the implementations of neural networks show, changes in the weight of any synaptic connection happen only in small increments. Thus, the trajectory of the weight vector of the learning system approximates a continuous path. In this sense, development is a continuous process.

Though learning and conceptual development are better described, in PDP, by reference to the weights of the hidden units and the weight space they determine, the traditional ìconceptual frameworkî of the system is better described by reference to another space, namely the space of activation of the hidden units of the system. This is so, because the ìcluster analysisî of the activation patterns of these units allows us to describe in semantic terms the behavior of the system. This ìcluster analysisî reveals that the activation space of the hidden units of the system, is partitioned in sub-areas in which prototypes are stored, and these prototypes are the best approximation to the traditional ëconceptsí. Thus, the partitioned activation space corresponds roughly to the traditional ìconceptual frameworkî.

It has been shown (Rumelhart and McLelland, 1986; Hinton and Sejnowski, 1986) that small, continuous, changes in the weight values of the hidden units of the system can occasionally produce abrupt and large changes in the partitions in the activation space. These changes are manifested by a discontinuous, stage-like, increase of the level of performance of the system in some field of competence or other. Since development is traditionally closely related to the level of performance in certain tasks, development appears to be a discontinuous, and stage-like, process. Therefore, in connectionist theory, development is seen as a continuous process in the level of the mechanism which causes it (i. e., in the level of weight space), whereas in another level (i. e., in the level of the activation space), it is seen as a discontinuous, abrupt process.

This discussion pertains to connectionist systems that have a fixed architecture. There are systems, however, that start with a minimal architecture and, as they learn, alter this architecture to satisfy the need for an increased representational capacity or for an increased specification of processing. In the first category we have the ëcascade correlationí connectionist networks that start with no hidden units and as the demands of handling the input increase they recruit hidden units. Such models have been developed by Shultz (Shultz & Schmidt, 1991; Shultz, Schmidt, Buckingham, & Mareschal, 1995) to simulate the training of networks in various different cognitive tasks, such as, Sieglerís (1976, 1981) balance scale tasks, tasks of seriation, etc. In the second category we have networks that prune their connections to increase their specificity (meiosis networks developed by Hanson, 1990). Note that this connection pruning parallels the selection and elimination of synapses observed in learning and development of the real brain (Changeux and Danchin, 1976; Changeux and Dehaene, 1989; Changeux, 1985; Edelman, 1987; Gazzaniga, 1983; Kerszberg, Dehaene, & Changeux, 1992). In connectionist systems with variable structure, learning is accompanied by a qualitative change as well, besides the quantitative one regarding the changes in connection weights. This qualitative change is none other than the change in architecture and the addition, or reduction, of new units and connections. Thus, at the level of the dynamics of the change, change is both continuous and discontinuous, that is both quantitative and qualitative. In fact, Shultz (Shultz & Schmidt, 1991) suggest that the quantitative phase of error reduction and weight change may correspond to Piagetís ëassimilationí of information in a pre-existing structure, whereas the qualitative change of unit and connection change may correspond to Piagetís ëaccommodationí of the structure to handle unassimilated information.

Relationships With Cognitive Neuroscience

The relationships between our theory and cognitive neuroscience need special attention because there are findings and models which suggest interesting parallels. For instance, blindsight phenomena constitute a strong support for the distinction between an environment-oriented (the SCSs) and a knowing-oriented (the hypercognitive systems) knowing level. The first involves states about person-environment encounters and is able to regulate itself but it does not involve experience or states about these states. The knowing-oriented level observes the environment-oriented level, thereby creating knowledge about knowledge. In support of this distinction, there are patients who can reach for an object but they state that they cannot see it, if it is placed in their blind spot which was caused by a lesion in the visual cortex (Weiskrantz, 1986). Moreover, there is evidence that amnesics can be taught new information without being aware of knowing it (Shacter & Tulving, 1994). Finally, there is evidence indicating that autistic individuals do not lack the capacity of building environment-oriented skills and knowledge but they lack the capacity to maintain a theory of mind and to reflect on their own thought processes (Baron-Cohen, 1995). In line with this clinical evidence, neuroanatomical and modern brain imaging techniques suggest that working memory (the processing system), problem-specific processes (the SCSs), and awareness about them (the hypercognitive system) are located in the prefrontal cortex (Nelson, 1995), various areas of the occipital (visual), the temporal or the perietal cortex (verbal and numerical) (Dehaene & Cohen, 1995), and the frontal cortex (Petrides, 1996), respectively. As whole, these findings suggest that the three-level architecture proposed here is neurologically sound.

It is also notable that our assumptions about the dynamics of development are consistent with recent developments in the study of brain development and the brain development-cognitive development relations (Fischer & Rose, 1994; Thatcher, 1994). Specifically, it was found that major changes in the type of representations that the mind can build occur in the same time window with changes in the relative EEG power in the frontal-temporal area of the brain. These changes were observed for the 12 to 18 months of age change, which, in Piagetian terms, leads from sensorimotor to representational intelligence and also for the 10 to 11 years change, which leads from concrete to abstract thought. After each of these major changes in the brain a series of other EEG power spurts were found to cycle over other areas of the brain, that is, from the occipital-parietal to the temporal to the central. These changes seemed to take place at those years of age at which there is a change in the complexity of mental units that the child can construct by integrating simpler but representationally similar units. It is commonly recognized that the frontal cortex is involved in the control processes which are responsible for the coordination of independent or competing activities (Case, 1992; Petrides, 1996) and also for the detection and encoding of novelty (Tulving, Kapur, Craik, Moscovitch, & Houle, 1994). According to Fischer and Rose (1994), this coincidence between changes in the type of controls over skills that one can construct and the type of changes in the connectivity between different areas of the brain (long-distance, global connections vs. local connections between adjacent areas) indicates that different types of cognitive change are associated with different types of brain changes. These sequence of changes in the development of the brain suggests an interesting parrallel with the mechanisms of change proposed here. That is, it might be the case that long-distance global connections correspond to mechanisms underlying broad changes in cognitive units, such as metarepresentation and bridging, whereas more local connections are related to mechanisms underlying more limited cogntive constructions, such as interweaving or fusion.

There is another point of interest in Fischer and Roseís (1994) view about brain change. Specifically, they point out that concurrence in change over different areas of the brain does not necessarily imply commonality. Concurrence in the change patterns of ìindependent growers arises from the dynamics of growth, not from a singe common cognitive of neural process.... Indeed, contrary to common assumptions, concurrence is not at all contradictory with localization and domain specificityî (p. 4-5). This condition of the brain is in line with the assumption of the present theory that centrally initiated changes may then evolve locally and independently of each other. Therefore, the development of the brain seems to involve both continuous and discontinuous, general and local, changes which seem to correspond to the continuous and discontinuous and the domain-free and the domain-specific changes of cognitive functions. All four different types of change seem able to be modeled by modern dynamic systems theory (Case et al, 1996; van Geert, 1994).

Summary and Conclusions

This paper elaborated on the architecture of the human mind, its development, and the interaction between architecture and development. The ideas advanced here are summarized below. The general implications of these ideas for developmental theories are also discussed.

Two claims were advanced about the architecture of the mind. First, that the mind is a hierarchical system. The reader is reminded that the theory discerns two knowing levels, one environment-oriented and one self-oriented, and a processing level where the two knowing levels send their activated elements for processing. Second, it was also argued that the mind is multistructural. That is, that all three levels involve multiple structures and processes. Therefore, this theory predicts that performance on any task is a function of the three dimensions of the processing system, the SCS-specific processes pertaining to the SCS(s) brought to bear on the task at hand, and the systems involved in the hypercognitive system. Axiomatically, this prediction can be stated as follows:

$$T_i = f\ E\ (PS_{(s,\ c,\ wm)},\ SCS_{(cr,\ cm)},\ HP_{(ThI,\ ThC,\ CSI)}).$$

Where T_i stands for performance on any task *i* that can be addressed to a person; E stands for the experience that the person has with the particular task and it can be defined in reference to parameters such as familiarity, practice, etc.; PS stands for the processing system and s, c, and wm stand for the three dimensions of the processing system, that is speed, control, and working memory respectively; SCS stands for the SCSs and cr and cm stand for the core of general processes that define an SCS and the various component processes that may also be involved in addition to the core processes, respectively; HP stands for the hypercognitive system and ThI, ThC, and CSI stand for oneís theory of intelligence, theory of cognition, and cognitive self-image respectively. Attention is drawn to the experiential factor. Involving this factor is important because the degree of involvement of each of the other factors is moderated to a certain degree by the experience of the person with the task. For example, the involvement of the two domain-general systems may be higher when familiarity with a task category is limited; latter, when SCS-specific skills are build up as a result of familiarity and practice the involvement of the general systems decreases and that of the specialized systems increases.

Developmental change can be defined in terms of three questions: why does it occur, how is it effected, when does it take place? Our answer to the *why* question is at one and the same time nativist and constructivist. That is, we believe that change starts from constructs which were made to abstract particular meaning from particular patterns of information in the environment. Karmiloff-Smith (1992) would say that it starts from ready-made attention biases. The psyho-ecological tuning which underlies these attention biases, however, is frequently jeopardized by variations in the environment itself, variations in the way the environment is recorded by the mind over time, variations in the functioning of the mind itself over time, and variations between interacting minds. These variations cause instabilities and uncertainties, and thereby inefficiencies in or queries about functioning, which call for changes that would increase stability, decrease uncertainty, improve the efficiency of the system, or enhance understanding and congruence both within and between minds. In this process, the system is directed by primitives which ensure that new constructions will continue to somehow represent the true state of the world. The system also builds the new by calling upon related representations and by varying them until to produce the best-fitting variation.

How is developmental change effected? Through a similization-binding process that integrates representations and / or mental actions with each other and with a goal that defines the value of the products of this similization-binding process. The closer they are to the goal the higher their value. Analogical reasoning was considered to be the mechanism underlying this similization-binding process. However, this basic mechanism of change is itself subject to variations depending upon the type of change to be effected. The basic criterion directing these variations is whether the to-be-constructed unit belongs to the same or to a different domain of thought or whether it resides at the same or a different level of the mental architecture. This is necessary because the products of development should not endanger the very structure of the system. Thus, the various mechanisms discussed above (bridging, interweaving, fusion, differentiation and refinement) are actually marking processes that mark the identity and the status of the products of change relative to the architecture of mind. In addition, they may involve different strategies in producing variations, effecting the mapping process, and generate symbols to individuate the products of the process.

Specifying when developmental change occurs is also a complex issue. Different types of change occur at different phases of development. A change across hierarchical levels occurs when the transformations in the changeinitiating level have acquired a minimum of momentum such that they can affect the other levels. Here one can involve the earthquake example. Tremor at the surface of the earth does not begin until the energy in the underlying causal layer exceeds a certain limit. Likewise, change within layers or structures, which comes from the integration of more basic units, cannot occur unless these integral units are functional enough to be used as building blocks for the constructions of another mental unit.

Thus, the theory predicts that different types of interactions between the levels and systems of mind produce different types of change which are effected through different mechanisms. That is, interactions between the three levels of the mental architecture produce major reorganizations and probably major shifts in the rate and scope of change. Interactions between systems within a level produce smaller reorganizations and smaller shifts in the rate of change.

Obviously, development affects architecture as much as architecture affects development. That is, the new units created as a result of development alter considerably the communication between layers and structures. The new units function as carriers of meaning from the one structure to the other within the levels (e.g., across SCSs or across hypercognitive models) or across levels (i.e., from the environment-oriented to the self-oriented system). In their capacity of transferring meaning, the mechanisms of change were called ideotransmitters. That is, they induce the person to see the objects or relations which are characteristic of one domain of the environment or the self from the perspective of the objects or the relations which reside in other domains. We have shown that major changes of this kind are reflected in perturbations in the relations between the levels of the mental architecture (Demetriou et al., submitted-b).

The assumptions above do bear clear implications for learning. Specifically, they suggest that learning can take place at any of the hierarchical levels or systems of the mind. However, the transfer of learning effects to domains other than the one originally affected would differ depending upon the nature of this domain. Specifically, domain-specific learning refers to changes in the knowledge, processes, and skills which are activated by particular domains of the environment and which are required to cope with the particular demands posed by these environments. Thus, domain-specific learning springs from, and affects the functioning of, the domain-specific modules and it is effected by mechanisms which ensure that the newly generated skills and concepts will honor the particular domains. Thus, training which aims at the construction of domain-specific skills has limited transfer, as it was found by our (Demetriou et al., 1993a) and othersí research (see Case et al., 1996). Domain-general learning refers to changes in the knowledge, processes, and skills which are concerned with knowing and handling the functioning of the mind itself and it involves, somehow, the hypercognitive system. Thus, domain-general learning involves mechanisms, such as metarepresentation, that generate and refine general patterns of mental action, such as logical reasoning. As a result, training which is directed at the construction of patterns of this kind must have effects that generalize over different domains, as it was found by Adey and Shayer (1992).

What then is the main message of this article? We want to focus attention on the implications that this model has for our conception of the nature of development and learning. Due to the influence of Piaget and Vygotsky, the giants of the field, we almost unquestionably accept that development and learning are constructive. Even modern students of the neurological bases of cognitive development, to paraphrase the title of a recent article by Quartz and Sejnowski (1997), feel the need to issue ìa constructivist manifestoî about the ìneural basis of cognitive developmentî. The model presented here is not compatible with this wild conception of constructivism. The reader is reminded that, according to our model, the mind involves multiple levels and systems which are both distinct and synergistically functioning so that development and learning in any one of them is constrained by the condition of the others. Thus, while development and learning in any SCS may be constructive to a certain extend, what can be constructed and how this is done are constrained by the condition of other SCSs, the processing system, and the hypercognitive system. Development and learning in the hypercognitive system are certainly constructive, for they represent the mindís own attempt to map and regulate itself. However, what can be mapped and how it can be regulated are largely constrained by the to-be-mapped and regulated constructs themselves and the processing system. Moreover, each type of construction takes place through different mechanisms which may themeselves be reciprocally constrained. Thus, it is time to abandon the Piagetian and Vygotskian myth of wild constructivism and consider seriously a model of *constrained constructivism*. In fact, if we are to understand how the mind is formed during development and learning we must pinpoint how development and learning in each of the systems constrains and is constrained by development and learning in every other system with which it synergistically interacts and find out how we can remove or ameliorate these constraints, when necessary, and build onto them, when possible. The model proposed here is a first step in this direction.

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Notes

1. Early in the formulation of the present theory, the term ìcapacity spheresî was used to denote systems of thought which were regarded to be functionally and developmental autonomous of each other (Demetriou and Efklides, 1981, 1987). The intention in using this term was to convey the assumption that these systems may be dimensions of more or less stable individual differences. Subsequently, and after long discussions with Robbie Case, we shifted to the term ìspecialized structural systemsî (Demetriou et al, 1993) to denote the same constructs. The aim was twofold. That is, first, to differentiate the environment-oriented domains of thought from processing capacity itself and, second, to convey the assumption, which then tended to win, that these systems are environmentally and culturally determined. Now we decided to merge the two terms into a hybrid one: ìspecialized capacity systemsî. This term denotes our present conviction that there is something innate and hardwired in these systems which may coexist with other environmentally and culturally determined constituents.

Table 1

The modal characteristics of the mechanisms of change

Mechanisms	Type and direction of change	Connectionist account of the mechanisms
Mechanisms producing change within the same SCSs		
Refinement & elimination	Abandonment of unwanted mental units.	Reduction or elimination of some weights and strengthening of others.
Differentiation	Increasing focusing of mental units.	Splitting of the activation space and redistribution of weight strengths.
Fusion	Construction of new mental units by integrating available units within the same sub-module.	The activation space that corresponds to the new mental unit replaces the activation space of the constituent units.
Interweaving	Construction of new mental units by integrating available units within the same system.	Basically the same type of repartition of the activation space as in fusion, except that here the new area takes up space from, and thereby reduces, the activation space of the constituent units.
Mechanisms producing change across different SCSs		
Bridging	Construction of new mental units from different systems.	The activation space is repartitionned. The new space is superimposed on those that have been combined to generate it.
Hypermechanisms		
Metarepresentation	Construction of new inference patterns and new strategies for the manipulation of representations as a result of self-monitoring and self-manipulation of representations and self-regulatory experiences	Detection of first or higher order similarities in the input signal and to the partition of the activation space of the hidden units according to these similarities.
Symbolic individuation	Association of the new units with symbols.	It involves construction of new hidden units or strengthening of some weights .

A. Environment-oriented system
systems (and abilities)

B. Processing
C. Long-term

hypercognition

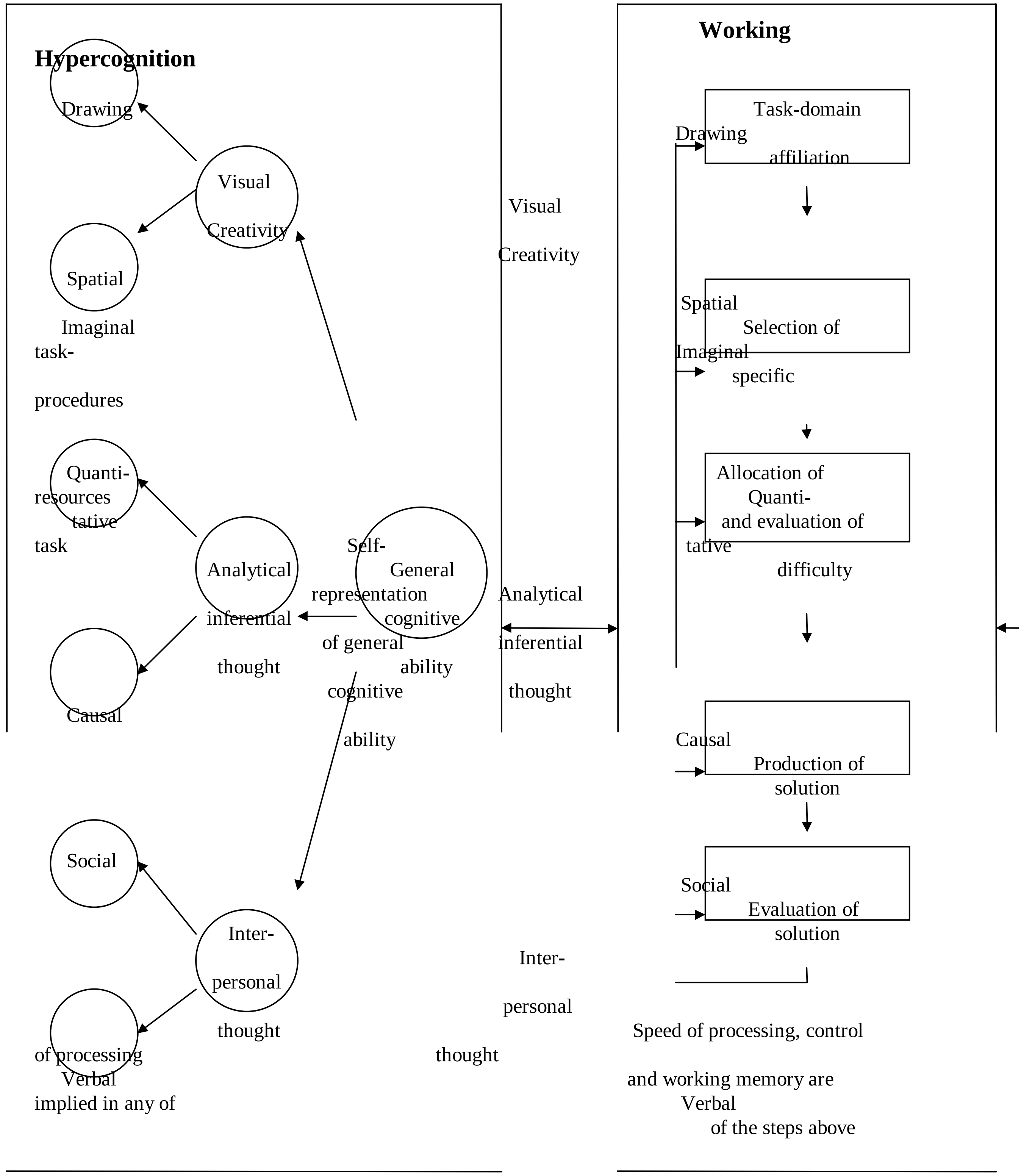

Figure 1. The three levels of mind and their internal structure.

Note: Attention is drawn to the equivalence between the structure of abilities in the environment-oriented level and their representation in the hypercognitive system. Attention is also drawn to the assumption that the processing system is occupied by the self-monitoring and self-regulation processes involved in working hypercognition.