STRUCTURAL AND DEVELOPMENTAL DIMENSIONS OF HUMAN INFORMATION PROCESSING: LONGITUDINAL AND CROSS-CULTURAL EVIDENCE

Maria Platsidou, Andreas Demetriou, &
Zhang Xiang Kui

THE BASIC PREMISES OF THE MODEL

This paper aims to present a theory which has been proposed by Demetriou and his colleagues (Demetriou, Efklides, & Platsidou, 1993a) with the aim to offer a comprehensive interpretation of the structure, the functions and the development of the human mind which is more congruent with empirical evidence than other alternative theories of cognitive development. Like any other theory of cognitive development, this theory deals with three fundamental questions regarding the human mind. Specifically, it aims to highlight (i) the structural organization of our cognitive system, (ii) how it develops with age, and (iii) which mechanisms are responsible for the kind of structures and the developmental patterns we observe. This theory is one among several alternative theories of cognitive development which were proposed after the fall of the Piagetian paradigm (i.e., Case, 1985, 1992; Fischer, 1980; Halford, 1993; Pascual-Leone, 1970).

The origins of this theory may be traced almost 20 years back, when Demetriou and Efklides first started in the University of Thessaloniki their studies on the structure of the human mind (Demetriou & Efklides, 1985, 1988, 1989). Since then, they have continuously worked in this field with their colleagues (Demetriou & Efklides, 1994; Demetriou, Efklides, Papadaki, Papantoniou, Economou, 1993b; Demetriou, Efklides, & Platsidou, 1993a; Demetriou, Gustafsson, Efklides, & Platsidou, 1992; Demetriou, Platsidou, Efklides, Metallidou, & Shayer, 1991; Efklides, Demetriou, & Metallidou, 1994). The theoretical model, which grew out of this research endeavour, is still under formation (i.e., revised, transformed, elaborated, enriched, and expanded). Thus, in the pages below we shall attempt to outline the postulates, hypotheses and findings of the theory that are presently accepted in Thessaloniki.

According to Demetriou (1993), this theory draws from three different traditions in psychology. The concern about the nature of knowledge and understanding of different phases of development comes from the Piagetian tradition. The methods for the delimitation of cognitive structures and the specification of the individual differences both in structure and development come from the psychometric tradition. Finally, the modelling of the processing characteristics and requirements of the different structures come from moderm cognitive psychology, the theory of human information processing in particular. In other words, this theory may be seen as an attempt to integrate the strong points of the developmental, the psychometric and the cognitivist tradition into a comprehensive system.

The paper will be organized in two parts: In the first part, we shall outline the general architecture of mind as proposed by the theory. In the second part, we shall focus on the structural constituents of one of the levels of mental architecture, namely, the system which is responsible for information processing. Specifically, we shall present a series of experiments conducted to specify the structure and development of this system and its relations to the other systems described by the theory.

PART 1

The architecture of the developing human mind

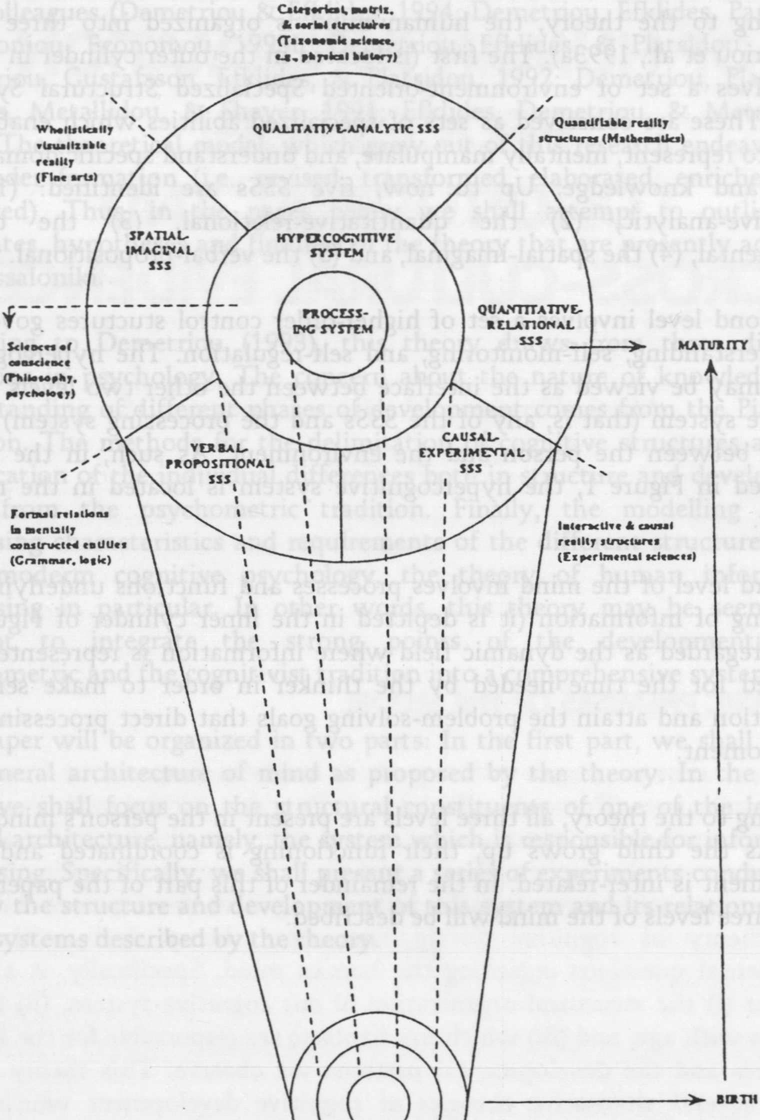
According to the theory, the human mind is organized into three levels (Demetriou et al., 1993a). The first (is located in the outer cylinder in Figure 1) involves a set of environment-oriented Specialized Structural Systems (SSSs). These are conceived as sets of specialized abilities which enable the person to represent, mentally manipulate, and understand specific domains of reality and knowledge. Up to now, five SSSs are identified: (1) the qualitative-analytic, (2) the quantitative-relational, (3) the causal-experimental, (4) the spatial-imaginal, and (5) the verbal-propositional.

The second level involves a set of higher-order control stuctures governing self-understanding, self-monitoring, and self-regulation. The hypercognitive system may be viewed as the interface between the other two levels of the cognitive system (that is, any of the SSSs and the processing system) or, in general, between the person and the environment. As such, in the model illustrated in Figure 1, the hypercognitive system is located in the middle cylinder.

The third level of the mind involves processes and functions underlying the processing of information (it is depicted in the inner cylinder of Figure 1). This is regarded as the dynamic field where information is represented and processed for the time needed by the thinker in order to make sense of information and attain the problem-solving goals that direct processing at a given moment.

According to the theory, all three levels are present in the person's mind from birth. As the child grows up, their functioning is coordinated and their development is inter-related. In the remainder of this part of the paper, each of the three levels of the mind will be described.

Figure 1. The general model of developing mind (from Demetriou et al., 1993a).



The SSSs: Structure and domains of application

The first level involves a set of specialized structural systems (SSSs). Each of the SSSs is considered to be a universe of knowledge acquisition, representation and processing schemes or components. These are fused together under the guidance of the principles which govern the functioning and organization of our cognitive apparatus (Demetriou et al., 1993a). These are the principles of domain specificity, procedural-computational specificity, symbolic bias, subjective distinctness of cognitive schemes or components, and developmental variation. Each of these principles implies, respectively, that if several component abilities are concerned with the same reality domain, bear on the same formal and procedural properties, tend to be represented through the same symbol system, and are felt or recognized by the thinker herself as being similar, then it is assumed that they will be coordinated to form an SSS. Specifically, the first principle (*domain specificity*) implies that component abilities which are concerned with the same reality domain tend to be integrated into the same SSS. According to the principle of *procedural-computational specificity*, the mental acts and computational characteristics of each SSS bear on common formal and procedural properties that preserve the domain's structural and dynamic characteristics. In order to function efficiently, each SSS 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 (the principle of *symbolic bias*). The principle of *self-mapping (subjective distinctness)* states that cognitive experiences which differ between each other according to the three principles above are felt or cognized by the person as distinct of each other; otherwise, they are felt to be equivalent. On the basis of these feelings, the person gradually constructs mental maps of cognitive processes which reflect their objective organization. The principle of *developmental variation* states that the different SSSs and even the different components within an SSS may follow partially independent developmental trajectories. This is due to the fact that it is unlikely that a person would either distribute his time evenly across different reality domains or never come across a given domain. Preferences and motivation play an important role in person's involvement with each reality domain or SSS (Demetriou, Pachaury, Metallidou, Kazi, in press).

It has already been mentioned that five SSSs have beed identified until now. A series of studies have investigated the composition, development, and domain affiliation of each SSS. The brief description below is based on these studies.

The qualitative-analytic SSS specializes on the representation and processing of similarity and difference relations (Demetriou et al., 1993a). Its functioning is based on the specification and disentangling of the various properties that may co-define the objects of reality. Once this is possible, the various properties can be treated as pure objects of thought activity (e.g., the "greenness" or the "redness", the "squareness" or the "circularness" of the objects are combined to build the concepts of green squares and circles and red squares and circles). Thus, this SSS is the basic production mechanism underlying the representation and processing of categorical and serial structures. The field of formal knowledge related to this SSS is taxonomic science, for example, physical history.

The spatial-imaginal SSS is directed to those aspects of reality which can be visualized by the mind's eye as integral wholes and processed as such. This system involves abilities such as mental rotation, image integration, and image reconstruction. Evidently, this SSS comes out of and directs the activities which are related to location and orientation in space. Fine arts are evidently related to this SSS (Demetriou & Efklides, 1989; Demetriou, Loizos, & Efklides, in preparation).

The quantitative-relational SSS is concerned with the quantifiable aspects of reality. This system involves three sets of abilities. (a) *Abilities of quantitative specification and representation*: Counting acts, such as pointing, and quantification symbols may be taken as the overt manifestations of these abilities. These indicate that the system is prone to quantify the environment. (b) *Abilities of dimensional-directional construction*: They refer to operations enabling the person to specify different types of quantitative relations. For instance, increase or decrease which may be regular or irregular, linear or curvilinear, etc. These abilities underly the dimensionalization of reality. (c) *Abilities of dimensional-directional coordination:* These enable the thinker to grasp and specify inter-dimensional relations. They are the basis of complex mathematical thinking such as proportional reasoning (Demetriou et al., 1991; Demetriou et al., in press).

The causal-experimental SSS is applied on causal reality structures. It is directed at disembodying cause-effect relations out of broader networks of phenomenally relevant but essentially irrelevant relations in regard to a phenomenon, and at building models representing these networks of relations. *Combinatorial abilities* form the cornerstone of this SSS. *Hypothesis formation abilities* enable the person to induce predictions about possible causal connections on the basis of data patterns. *Experimentation abilities* enable the person to "materialize" hypotheses in the form of experiments. The isolation-of-variable ability is a good example of this set of abilities. Finally, *model construction abilities* enable the person to properly map the results of experimentation with the original hypothesis in order to arrive at an acceptable interpretative framework or theory. Obviously, all experimental sciences are related to this SSS (Demetriou et al., 1993b).

The last is the verbal-propositional SSS which is concerned with the formal relations between mental elements. The main characteristic of this SSS is the ability to differentiate the contextual from the formal elements of a series of statements and operate on the latter. Grammar and logic are some of the relevant knowledge fields (Efklides, Demetriou, & Metallidou, 1994).

It must be noted that, besides the five SSSs discussed here, there may also be other SSSs in operation that are yet to be discovered, such as a musical or a bodily-kinesthetic SSS, as Gardner (1983) maintained. In fact, our recent studies suggested that social understanding and drawing have all properties that would justify considering them as SSSs equivalent to these discussed above (Demetriou, Kazi, Platsidou, Sirmali, Efklides, & Kiosseoglou, submitted).

The hypercognitive system: Structure and functioning

The second level involves the hypercognitive system. This is a domain-general system that involves models, rules, and strategies, underlying self-understanding, self-monitoring and self-regulation. In other words, these models, rules, and strategies are the means which enable the person to make meaning out of and regulate both her own cognitive activity and her interactions with the environment. For this reason, it is regarded as the interface between (a) the person and the environment, (b) any of the SSSs, and (c) the various SSSs and the processing system to be specified below.

Thus, what has come to be known as metacognition is part of the hypercognitive system. The term metacognition conveys the assumption that the functions associated with it come after cognition. However, it has been shown that these functions may as well come before and shape cognition (Demetriou & Efklides, 1989). The term hypercognition is neutral in this regard and, thus, it can accomodates both aspects. Moreover, hypercognition is a more accurate term, as it refers to functions applied on the other cognitive systems. Also, for reasons that will become obvious in the following pages, concepts like "personal theory of mind", and "implicit theories of intelligence" are included in the hypercognitive system (Demetriou et al., 1993a; Demetriou, Makris, & Adecoya, 1992).

This system seems to exert its control on the functioning of intelligence at two different levels. At a macro-functional level, hypercognition frames the person's general orientation to how reality is to be represented and processed. Thus, at this level, the system refers to the person's ideas about intellectual functioning. This may involve three integral components: (a) *A model of intelligence* which specifies what is smart or dull in a given environment. (b) *A model of cognitive organization and functioning* which specifies what cognitive functions exist (for example, memory vs. perception or remembering vs. thought) and how they can be efficiently used (i.e., rehearsal is effective for a short list of digits but organization for a long one). The «theory of mind» which refers to the person's understanding that behaviour is mediated by mental states (Wellman, 1990) is part of this model. (c) *A model of oneself as an intelligent being:* This model specifies the person's self-image and preferences as a cognitive being. According to Demetriou et al. (1993a), the hypercognitive system is operational from a very early age, if not from birth. The claim is in agreement with recent views (e.g., Karmiloff-Smith, 1992) that self-awareness and self-regulation are biologically given and located in specific areas of the brain.

At a micro-functional level, the hypercognitive system controls on-line cognitive functioning. As such, this system is involved in making decisions of three kinds: (a) The first set of decisions refers to the SSS-task affiliation. This is a group of decisions aiming to ensure that the right SSS and the most relevant task-specific schemes will be brought to bear on the task at hand. (b) The second set of decisions refers to the efficient use of these schemes in relation to the resources of the processing system. (c) The third set of decisions aims to evaluate the outcomes of processing and project these evaluations on the macrofunctional level. Thus, every problem solving attempt contributes to the refinement of the mind's hypercognitive maps which will be called upon during the future problem solving attempts.

The information processing system: structure and development

To be able to use efficiently any of the SSSs, one would have to be able to keep in mind the goal set to oneself and also sets of representations related to the information involved in the problem to be solved. This minimum requirement is necessary for the solution of any relatively complex problem because it enables the thinker to chose an optimum solution among alternatives. However, if this requirement is to be met, the person must posses a system in which information can be represented and processed for the time needed to define the problem goal and envisage alternative solutions to it. This is the processing system. This system is defined as a dynamic field where information is represented (that is, encoded, sorted out, and kept active) and processed (that is, connected, compared, transformed, or combined) for as long as it is required by the thinker in order to make sense of and use this information to attain a current mental goal (Demetriou, 1993). Understanding the nature and functioning of this system is important because it underlies practically any meaning making and problem solving endeavor to the one or the other extend. According to the theory, the processing system is defined in terms of three dimensions. That is, (i) processing speed, (ii) control of processing, and (iii) storage (Demetriou et al., 1993a). Speed of processing refers to the maximum speed at which a given mental act may be efficiently executed. Control of processing refers to a mechanism which functions under the guidance of the task-goal like a filter permitting only goal relevant schemes to enter processing space. Storage refers to the maximum number of schemes that the mind can efficiently activate at a given moment.

These three dimensions are considered to be both distinct of each other and interrelated. That is, the faster one is as a processor, the more information units one would be able to process in a standard time unit. Therefore, the more efficient one would eventually be in sorting out the goal-relevant from the goal-irrelevant schemes. In turn, the more efficient one is in regard to speed and control of processing, the better one would be in using one's storage potential. This is so because the right information units will occupy this potential for the minimum time required to grasp the concept defined by them and assemble the response needed (Demetriou, 1993). Furthermore, the theory assumes that improvement in the functioning of the processing system, caused by either development or practice, result in better problem-solving. In other words, changes in the processing system affect cognitive functioning at the level of the complex problems which have been of primary concern to Piaget, the psychometric theories of intelligence, or traditional cognitivist theories of problem-solving (Demetriou et al., 1993a). The studies to be described in Part II are directly concerned with the assumption of the theory about the processing system.

PART II

1st Study

In this part, two studies will be presented which were carried out to illuminate various aspects of the processing system. In the past, many investigators studied the information processing capacity. Although it is commonly accepted that processing capacity is a complex concept to be defined in reference to multiple parameters (Wickens, 1974), most theorists have focused only on single parameters. Pascual-Leone (1988) regarded mental power, which is equivalent to storage, as the general capacity which is responsible for activating and representing the problem goal and the problem-relevant schemes. He suggested that the development of mental power is the mechanism which drives cognitive development. Kail (1986; Kail & Salthouse, 1994) has extensively investigated the development of speed of processing in various task conditions but he never explicated how speed of processing may be related to cognitive development. Case's (1985) definition of capacity is partly similar to Pascual-Leone's. He has studied the development of storage space and its relations with speed of processing. In his theory, these parameters are interrelated. The more efficient a person becomes in processing information (that is, the faster he becomes in processing information), the larger is the number of units of information this person can store in working memeory. Schneider & Shiffrin (1977; Shiffrin & Schneider, 1977) have underscored the role of the control function in the information processing capacity. They proposed a two-process theory of human information processing; automatic processing is the activation of a learned sequence of elements in long-term memory that is initiated by appropriate inputs and then proceeds automatically, without subject control, without stressing the capacity limitations of the system and without necessarily demanding attention. Controlled processing is a temporary activation of a sequence of elements that can be set up quickly and easily but requires attention, is capacity limited, and is controlled by the subject.

From this short overview it is apparent that there is no comprehensive study of the interrelations which unite the three components into an integrated system. Nor are there any comprehensive studies of the dynamic relations between the three components and other cognitive processes underlying problem solving.

The first study to be described has been designed with the aim to contribute to this point (Demetriou et al., 1993a). Specifically, this study aimed, first, to investigate the individual status of each of the three dimensions of the processing system and specify their interrelations. Second, the study also aimed to examine the relations between these dimensions and one of the specialized structural systems described above. For the purposes of the present study the quantitative-relational SSS was involved.

METHOD

Participants

A sample of 65 participants was tested. Of these participants, 16, 17, 16, and 16 were, respectively, 8, 10, 12, and 14 years old. They were drawn from the third, the fifth, the seventh and the ninth school grade, respectively. Males and females were almost equally represented. The participants were Greeks and they came from upper-middle-class families. The participants were re-tested with the same tasks six months after the first testing. At the second testing, all participants had moved to the next school grade.

Tasks

The participants were tested with a series of task batteries addressed to the three dimensions of the processing system (that is, processing speed, control of processing, and working memory) and also to several of the abilities involved in the quantitative-relational SSS.

Speed and control of processing tasks. To measure processing speed and control of processing a Stroop-like task (Stroop, 1935) was devised (Demetriou et al., 1993a). In this task, participants were presented with a series of cards, each showing a word that was a color name. Each of the word-stimuli was presented in two conditions; in the compatible condition, the meaning of the word and the ink-color in which it was written was the same (e.g., the word "red" written in red). In the compatible condition, the meaning of the word and the ink-color were different (e.g., the word "red" written in green). In each condition, the participants were asked either to read the word or to name the ink-colour as fast as possible.

Response time in reading the word in the compatible condition was taken to measure speed of processing; response time in naming the ink-color in the incompatible condition was regarded as a measure of control of processing. According to previous research (Dyer, 1973; MacLeod, 1991), reading a word in the compatible condition is an automated response which is facilitated by the fact that both aspects of the stimulus (i.e., meaning and color) are the same. Thus, in this condition, response time in reading the word was taken to measure speed of processing. Conflict-raising stimuli, such as naming the ink-color in the incompatible condition, require control in the execusion of the response. That is, the person has to suppress the response to the irrelevant aspect of the stimulus, which is the more familiar one, in order to respond to the relevant but less familiar aspect (that is, naming the ink-color instead of reading the word). Thus, reaction time in naming the ink-color in the incompatible condition was regarded as a measure of control of processing (Jensen, 1965; Jensen & Rohwer, 1966).

Working memory tasks. Working memory was tested with two tests devised by Case (1985), the Counting Span Test (CST) and the Ratio Span Test (RST). Both tests assessed children's ability to store and recall a series of digits representing the results of counting. The tests involved a series of cards which were presented succesively in sets of 2 to7 cards. Each card depicted a number of red and green dots.

In the first test, participants were instructed to count the red dots only, store the resultant digit in memory, and recall the complete series of digits upon presentation of a white card. Thus, in each set 2, 3,..7 cards had to be counted before the presentation of the white card. According to Case's theory, counting is a dimensional operation. The second test was identical to the first, except that the participant was asked to evaluate, store, and recall the ratio between the red and the green dots. This is a vectorial operation in that it requires the person to coordinate two numerical dimensions rather than to work with just one. Performance on the two working memory tests was scored with two scores. Each score was equal to the highest level of items the participant succesfully recalled in each test. These scores were indicative of the partcipant's storage capacity on the dimensional and the vectorial developmental stage, respectively.

Quantitative-relational tasks. Three task batteries were used to test three of the component abilities of the quantitative-relational SSS (Demetriou et al., 1991). The first addressed the ability to perform the four basic arithmetic operations in combination to each other. Participants were given a series of standard arithmetic equations in which one or more arbitrary symbols were used to stand for one or more arithmetic operations to be performed on the numbers involved. The participant's task was to specify the missing operation(s), e.g., (i) 5*3=8, (ii) [3*5]*5=10, (iii) [3*2*4]*5=7, (iv) [3*2]*4=[12*1]*2. The items were made to tap four levels of difficulty, each corresponding to the number of the operations missing from the equation.

The second task addressed the ability to solve simple algebraic equations. The items also spanned four levels of difficulty. At the first level of difficulty, the solution could be directly deduced from the elements given or defined by operating on them (e.g., a+5=8, a=¿). The problems at the second level required coordination of two well-defined sructures so as to specify the value of a third unknown element (e.g., m=3n+1, n=4, m=¿). The third-level items required to operate on undefined structures (e.g., r=s+t, r+s+t=30, r=¿). The items on the fourth level required coordination of undefined structures and understanding of the role of letters as generalized numbers or symbols of variables (e.g., «when is it true that L+M+N=L+P+N ¿»).

The third task battery was addressed to proportional reasoning. Following Noelting (1980), in this task participants had to judge the relative intensity of the color of two mixtures involving part pure paint and part solvent. It involved items spanning four difficulty levels. In the first, the mixtures involved fully equivalent ratios (e.g., [1p,1s] : [2p,2s], each pair of numbers referring to the parts of paint (p) and solvent (s) in mixture A and B, respectively). The second level involved partially equivalent ratios (e.g., [4p,2s] : [2p,1s]). The third level involved ratios of ordered pairs with two corresponding terms being multiples of one another (e.g., [2p,1s] : [4p,3s]). The fourth level involved ratios without corresponding items (e.g., [5p,7s] : [3p,5s]). Thus, lower-level items provided intuitive support to the processing of the proportional relations involved, whereas higher-level items required exact quantification. Due to their difficulty, the second and the third task batteries were administered to the youngest group of participants only in the second testing.

RESULTS AND DISCUSSION

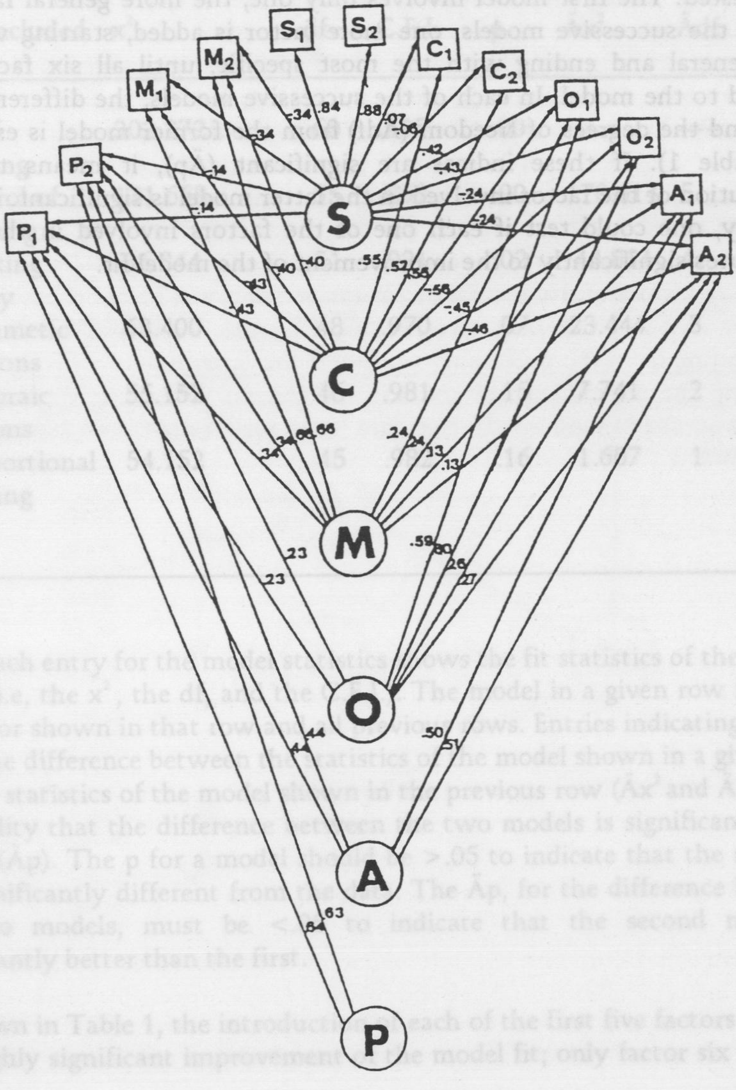
The structure of abilities

The structure and the relations between the three dimensions of the processing system and between these dimensions and the cognitive abilities tested in this study were explored by means of confirmatory factor analysis. For this purpose, the EQS statistical program was used (Bentler, 1989). Two models were found to fit the data equally well. Each one accomodates the data from a different point of view.

The first model was built according to the hypothesis that the tasks involved in the study represent processes ranging from the very basic level of the speed of processing to the advanced SSS-specific abilities in a clearly nested way. That is, there were simple tasks mapping only speed of processing (i.e., the compatible Stroop-like conditions). The incompatible Stroop tasks addresses primarily to control of processing but speed of processing was also required for the response to be efficiently executed. The working memory tasks were more demanded; it was assumed that they involved storage, plus the two basic processing components mentioned above, that is, speed and control of processing. In regard to the quantitative-relational batteries, the arithmetic operations task were taken to involve the basic quantitative ability to which it was addressed, plus the three dimensions of the processing system (i.e., processing speed, control of processing, and storage). The algebraic and the proportional reasoning tasks involved the processing dimensions, the basic arithmetic ability, and, at least, the specific ability they tested, namely, the algebraic and/or the proportional.

Thus, the model based on the above hypothesis was tested with the nested factor method (Gustafsson, 1994). This model, which is depicted in Figure 2, involves six factors: the measures representing processing speed were related to only one factor (S). The measures representing control of processing were related to the first factor and also to a second factor (C). The working memory tasks were related to these two factors plus a third factor (M). The tasks representing arithmetic operations were related to a fourth factor (O) in addition to the first three factors. Tasks representing the algebraic abilities were related, additionally, to a fifth factor (A) and tasks representing the proportional reasoning involved the above five plus a sixth factor (P). So defined, factors 1, 2, 3, 4, 5, and 6 can be taken to represent speed of processing, control of processing, memory, a basic quantitative-relational ability and two advanced quantitative-relational abillities (i.e., algebraic and proportional), respectively. The fit of the model to the data was excellent ($x^2(45)=54.152$, $p=0.160$, CFI=0.982).

Figure 2. The nested-factor model fitting subjects' performance on tasks assessing speed of processing (S), control of processing (C), working memory (M), and three quantitative-relational tasks, the arithmetic operations (O), the algebraic equations (A), and the proportional reasoning (P).



As it was said previously, this model was fitted with the nested factor method. This method was used because it provides a unique advantage. Not only it defines the factors which are mapped by the tasks (like every other factor model does), but it also gives a statistical criterion to estimate whether the contribution of each one of the factors involved in the model is significant. According to the procedure for testing nested factor models (Demetriou et al., 1993a; Gustafsson, 1994), a series of successive models has to be tested. The first model involves only one, the more general factor. In each of the successive models, one more factor is added, starting with the most general and ending with the most specific, until all six factors are included to the model. In each of the successive models, the difference of x^2 (Äx^2) and the degrees of freedom (Ädf) from the former model is estimated (see Table 1). If these indices are significant (Äp), it means that the contribution of the factor involved in the latter model is significant. Thus, in this way, one could test if each one of the factors involved in the model contributes significantly to the improvement of the model fit.

Table 1: Results of tests of the factor-nested models to the speed of processing, control of processing, working memory, and quantitative relational tasks.

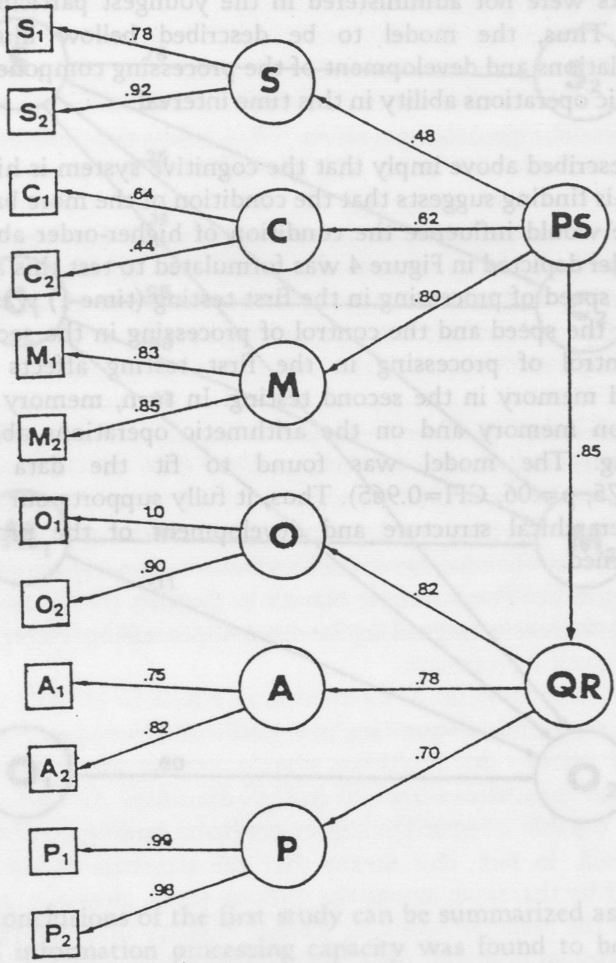
	Model Statistics				Change		
Factor included	x^2	df	C.F.I.	p	Äx^2	Ädf	Äp
speed of processing	302.272	60	.535	.00	-------	------	
+ control of processing	131.658	55	.853	.00	170.614	5	.005
+ working memory	86.844	51	.931	.02	44.814	4	.005
+ arithmetic operations	63.400	48	.970	.07	23.444	3	.005
+ algebraic equations	55.152	46	.981	.15	7.741	2	.025
+ proportional reasoning	54.152	45	.982	.16	1.607	1	N.S.

Note: Each entry for the model statistics shows the fit statistics of the models tested (i.e, the x^2, the df, and the C.F.I.). The model in a given row involves the factor shown in that row and all previous rows. Entries indicating change show the difference between the statistics of the model shown in a given row and the statistics of the model shown in the previous row (Äx^2 and Ädf). The probability that the difference between the two models is significant is also shown (Äp). The p for a model should be >.05 to indicate that the model is not significantly different from the data. The Äp, for the difference between the two models, must be <.05 to indicate that the second model is significantly better than the first.

As shown in Table 1, the introduction of each of the first five factors resulted in a highly significant improvement of the model fit; only factor six failed to result in a significant improvement of the model fit. This indicates that the domain-free dimensions of the processing system and the domain-specific abilities described by the theory have been identified in the data. Even more, it was also found that the abilities which reside at a hierarchical level involve the abilities of all lower levels plus the abilities which are specific to this level.

The second model aimed to specify the hierarchical structure of the cognitive system. It is based on the assumption that the three components of the processing system are organized into one general system and the three subsystems of the quantitative-relational SSS are organized into another general system. Two kinds of factors are involved in this model (it is shown in Figure 3). There is a set of first-order factors, which represent each of the component abilities tested: a speed of processing factor (S), a control of processing factor (C), a memory factor (M) and three specific quantitative-relational abilities factors (O, A, P). Moreover, there are two second order factors: a general processing system factor (PS) related to the three first-order processing factors and a general quantitative-relational factor (QR) related to the three first-order quantitative-relational factors. Besides, there is a causal path running from the processing system to the quantitative-relational factor, indicating the dependence of the SSS on general processing capacity. This model was also found to fit the data very well ($x^2(44)=47.256$, $p=0.341$, $CFI=0.994$).

Figure 3. The higher-order and causal model fitting performance on the speed of processing (S), control of processing (C), memory (M), and three quantitative-relational tasks (O, A, and P). The symbols PS and QR stand for the processing system and the quantitative-relational SSS, respectively.

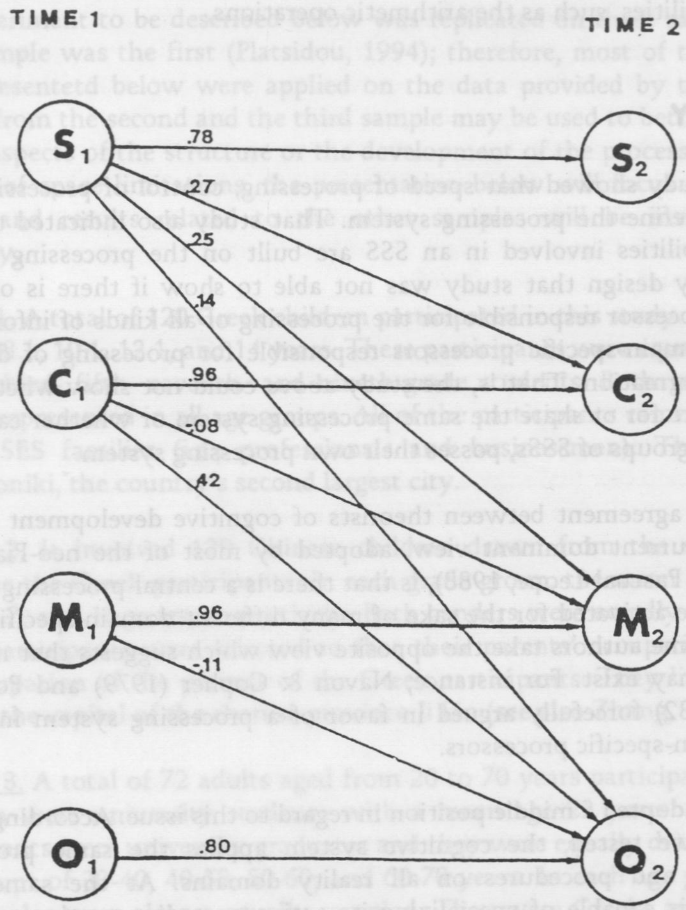


STRUCTURAL RELATIONS OVER TIME

Our experiment was repeated on the same participants six months later. All participants were tested twice with tasks addressed to the processing system. However, for practical reasons, only the arithmetic operations measurements are available in both testing waves; the algebraic and the proportional reasoning tasks were not administered in the youngest participants of the first testing. Thus, the model to be described bellow illustrates the hierarchical relations and development of the processing components and the basic arithmetic operations ability in this time interval.

The models described above imply that the cognitive system is hierarchically structured. This finding suggests that the condition of the more basic abilities earlier in time would influence the condition of higher-order abilities later. Thus, the model depicted in Figure 4 was formulated to test this assumption. In this model, speed of processing in the first testing (time 1) was defined to causally affect the speed and the control of processing in the second testing (time 2). Control of processing in the first testing affects control of processing and memory in the second testing. In turn, memory determines performance on memory and on the arithmetic operations ability in the second testing. The model was found to fit the data very well ($x^2(91)=112.875$, $p=.06$, CFI=0.965). Thus, it fully supports our assumption about the hierarchical structure and development of the processes and abilities concerned.

Figure 4. Causal relations between the speed of processing (S), the control of processing (C), the memory (M), and the arithmetic operations (O) factors across the two testing occasions. The values shown are standardized regression coefficients.



The main conclusions of the first study can be summarized as follows: First, the general information processing capacity was found to be composed of three components, namely speed and control of processing and storage. These are distinct processes but they are also interrelated in a hierarchical structure. Second, the study illuminated the relations between the processing system components and one of the SSSs, the quantitative-relational. Specifically, it was found that the processing system affects higher-order cognitive abilities, such as the quantitative-relational. Moreover, it was shown that the lower-level components of the processing system affect the construction and development of both, the higher-order processing components and the cognitive abilities, such as the arithmetic operations.

2ND STUDY

The first study showed that speed of processing, control of processing, and storage co-define the processing system. That study also indicated that the cognitive abilities involved in an SSS are built on the processing system. However, by design that study was not able to show if there is only one common processor responsible for the processing of all kinds of information or many domain-specific processors responsible for processing of different kinds of information. That is, the study above could not show whether the SSSs compete for or share the same processing system or whether each SSS, or probably groups of SSSs, posses their own processing system.

There is no agreement between theorists of cognitive development on this issue. The current dominant view, adopted by most of the neo-Piagetians (Case, 1992; Pascual-Leone, 1988), is that there is a central processing system which can be activated for the sake of many different domain-specific tasks. However, some authors take the opposite view which suggests that multiple processors may exist. For instance, Navon & Gopher (1979) and Posner & McLeod (1982) forcefully argued in favor of a processing system involving many domain-specific processors.

Our theory adopted a middle position in regard to this issue. According to the hypothesis we tested, the cognitive system applies the same processing mechanisms and procedures on all reality domains. At the same time, however, it is capable of specializing its action according to the particular domain processed. In fact, this means that the structure of the processing capacity should be the same across the various tasks, although performance as indicated by the response times or storage capacity may vary across tasks belonging to different domains. Moreover, differences in performance is likely to be attributed to the effect of the symbolic systems through which information is represented in different domains. To answer this question, the following study was carried out.

METHOD

Participants

The experiment to be described below was replicated on three samples. The main sample was the first (Platsidou, 1994); therefore, most of the analyses to be presentetd below were applied on the data provided by this sample. Results from the second and the third sample may be used to better highlight certain aspects of the structure or the development of the processing system. Because of space limitations, the presentation below will focus on the first sample and results related to the other samples will be invoked when necessary.

Sample 1. A total of 120 Greek children participated in this study. Their mean age was 8.1, 10.1, 12.1, and 14 years. These participants were equally sampled among third- fifth- seventh- and nineth-grade students. Both genders were equally represented in all age groups. All of the participants came from upper middle SES families (i.e., professionals and businessmen). They lived in Thessaloniki, the country's second largest city.

Sample 2. It involved 120 Chinese children drawn from the same school grades as the Greek participants. In each grade group, the mean age was 8.7, 10.9, 12.7, and 15 years, respectively. Both genders were equally represented. These participants were selected so that their parents' occupation matched the occupation of the parents of the Greek participants. They lived in Chan Chuan, the capital of the chenise province Ji Lin (see also Zhang, 1995).

Sample 3. A total of 72 adults aged from 20 to 70 years participated. Twelve of them were university students with a mean age 22 years. The rest 60 participants were university graduates and they were equally drawn from the age groups of 30-40, 40-50, 50-60, and 60-70 years. In each age group, males and females were almost equally sampled. They were Greeks and they lived in Thessaloniki.

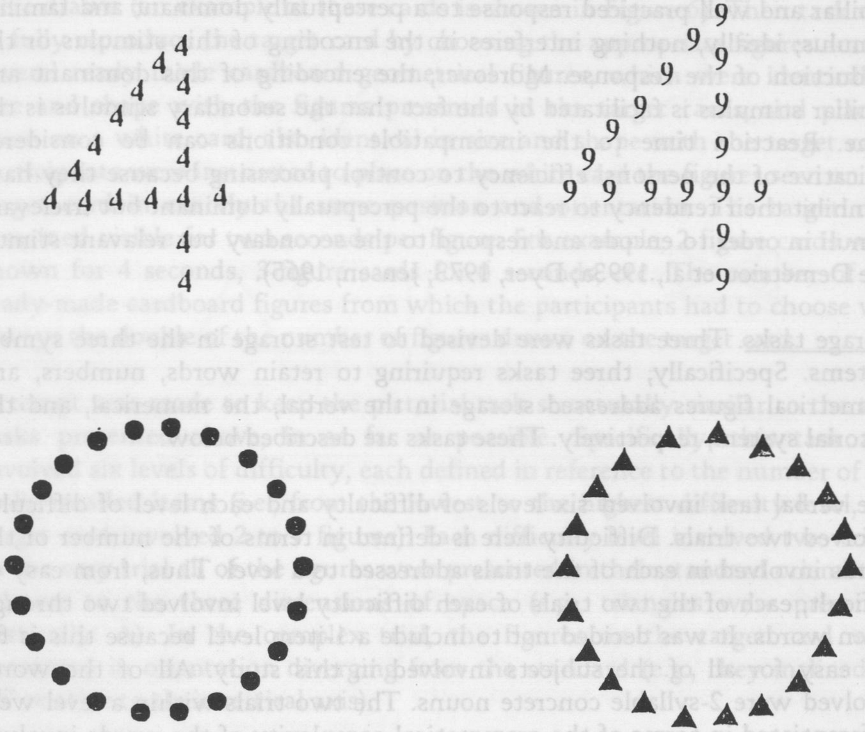
TASKS

All participants were tested with tasks addressed to speed of processing, control of processing, and storage. Each of these dimensions was examined by tasks tapping three symbol systems; namely, the verbal, the numerical and the pictorial symbol system. The participants were also tested with tasks addressed to component abilities involved in three SSSs; that is, the verbal-propositional, the quantitative-relational, and the spatial-imaginal SSS. According to the principle of symbolic bias, these SSSs are related to the verbal, the numerical, and the spatial-pictorial systems, respectively. The tasks are briefly described bellow; a more detailed description of these tasks may be found in Demetriou, Kazi, Platsidou, Sirmali, Efklides, & Kiosseoglou (submitted) and in Platsidou (1994).

Speed and control of processing tasks. A series of Stroop-like tasks were devised to measure processing speed and control of processing under three symbol systems, the verbal, the numerical and the pictorial. To measure the processing components in the verbal symbol system, we tested the subjects with the Stroop-like tasks used in Study 1. For the measurement in the other symbol systems we deviced two Stroop-like tasks.

In the numerical task, several «large» number digits were prepared which were composed of «small» digits (Navon, 1977; Stirling & Coltheart, 1977). Each digit-stimuli was presented in the compatible and the incompatible condition. In the former, the «large» digit was composed of the same «small» digit (e.g., a large 4 composed of small 4s); in the latter condition, the large digit was composed of other digits (e.g., a large 4 composed of small 9s). To measure speed of processing, the participants were asked to recognize the large number digit of the compatible stimuli. To measure control of processing, they were asked to recognize the small digit of the incompatible stimuli. Examples of this task is shown in Figure 5a.

Figure 5. Examples of the stimuli used in the Stroop-like tasks addressed to the numerical and the pictorial symbol systems, respectively.



The task addressed to the pictorial symbol system was identical to the arithmetic Stroop-like task (see Figure 5b). This task involved geometrical figures as stimuli (Kinchla, Solis-Macias, & Hoffman, 1983; Martin, 1979). In the compatible condition, a large figure was composed of the same small figure (e.g., a large circle outlined by small circles). In the incompatible condition, the large figure was composed of a different small figure (e.g., a large circle composed of small triangles). Recognition of the large figure in the compatible condition was regarded as a measure of speed of processing; recognition of the small figure in the incompatible condition was taken to measure control of processing.

Reaction time to all three types of the compatible conditions described above (i.e., using verbal, numerical, and figural stumuli) were taken to be indicative of a person's speed of processing because the persons are asked to provide a familiar and well practiced response to a perceptually dominant and familiar stimulus; ideally, nothing interferes in the encoding of this stimulus or the production of the response. Moreover, the encoding of this dominant and familiar stimulus is facilitated by the fact that the secondary stimulus is the same. Reaction time to the incompatible conditions can be considered indicative of the persons' efficiency to control processing because they have to inhibit their tendency to react to the perceptually dominant but irrelevant stimuli in order to encode and respond to the secondary but relavant stimuli (see Demetriou et al, 1993a; Dyer, 1973; Jensen, 1965).

Storage tasks. Three tasks were devised to test storage in the three symbol systems. Specifically, three tasks requiring to retain words, numbers, and geometrical figures addressed storage in the verbal, the numerical, and the pictorial system, respectively. These tasks are described below.

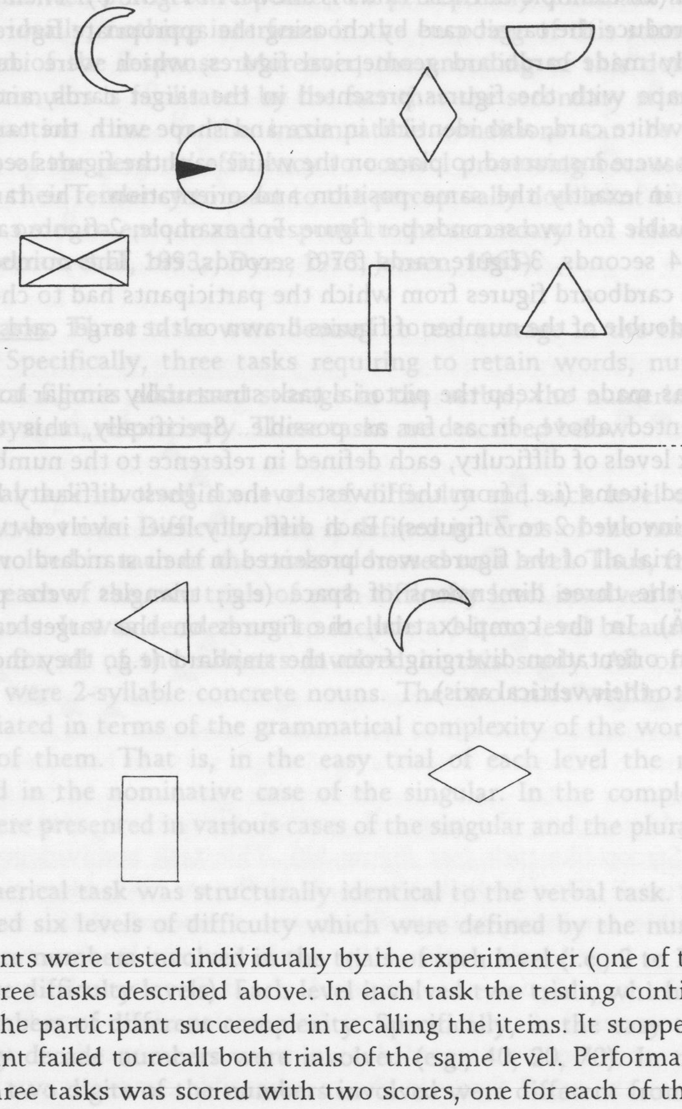
The verbal task involved six levels of difficulty and each level of difficulty involved two trials. Difficulty here is defined in terms of the number of the words involved in each of the trials addressed to a level. Thus, from easy to difficult, each of the two trials of each difficulty level involved two through seven words. It was decided not to include a 1-item level because this is far too easy for all of the subjects involved in this study. All of the words involved were 2-syllable concrete nouns. The two trials within a level were differentiated in terms of the grammatical complexity of the words involved in each of them. That is, in the easy trial of each level the nouns were presented in the nominative case of the singular. In the complex trial the nouns were presented in various cases of the singular and the plural.

The numerical task was structurally identical to the verbal task. Specifically, it involved six levels of difficulty which were defined by the number of the to-be-store numbers involved in the trials of each level (i.e., 2 to 7 for the six successive difficulty levels). Each level involved two trials, which involved 2-digit numbers of different complexity. Specifically, in the easy trial of each level only decade numbers were involved (e.g., 40, 20, 70). In the complex trial, the two digits of the numbers involved were different from each other (e.g., 84, 32, 57).

In the pictorial task the stimuli were presented visually and they had to be reproduced visuo-spatially. Specifically, in each of the items, the perticipants were shown a card (21 x 15 cm) on which a number of geometrical figures were drawn (an example of these cards is shown in Figure 6). Their task was to fully reproduce the target card by choosing the appropriate figures among several ready made cardboard geometrical figures, which were identical in size and shape with the figures presented in the target cards, and placing them on a white card, also identical in size and shape with the target card. Participants were instructed to place on the white card the figures seen on the target card in exactly the same position and orientation. The target card remained visible for two seconds per figure. For example, 2-figure cards were shown for 4 seconds, 3-figure cards for 6 seconds, etc. The number of the ready-made cardboard figures from which the participants had to choose was always the double of the number of figures drawn on the target card.

Attempt was made to keep the pictorial task structurally similar to the two tasks presented above, in as far as possible. Specifically, this task also involved six levels of difficulty, each defined in reference to the number of the to-be-recalled items (i.e., from the lowest to the highest difficulty level, the target card involved 2 to 7 figures). Each difficulty level involved two trials. In the easy trial all of the figures were presented in their standard orientation relative to the three dimensions of space (e.g., triangles were presented vertically: Ä). In the complex trial, the figures on the target card were presented in orientation diverging from the standard (e.g., they inclined by 45° relative to their vertical axis).

Figure 6. Examples of the stimuli used in the memory task addressed to the pictorial symbol system.



Participants were tested individually by the experimenter (one of the authors) on all three tasks described above. In each task the testing continued for as long as the participant succeeded in recalling the items. It stopped when the participant failed to recall both trials of the same level. Performance on each of the three tasks was scored with two scores, one for each of the two trials involved in the difficulty levels. Each of the two scores was equal to the number of the items involved in the highest level whose items were errorlessly recalled. For instance, a participant who obtained a score of 4 on a trial was able to recall correctly all four items involved in the given trial of the corresponding level and - ideally - the items involved in all lower levels of this trial.

Cognitive tasks. Three paper-and-pencil task batteries were used to test complex cognitive abilities. They were addressed to three SSSs, the verbal-propositional, the quantitative-relational, and the spatial-imaginal. These SSSs are related to the verbal, the arithmetic, and the pictorial symbol systems, respectively. Each task battery involved two tests; each of the two tests addressed a different component ability of the respective SSS.

In the verbal-propositional SSS, the first test was a verbal analogy test. Participants were presented with the following four verbal analogies:

1) ink : pen :: paint : ______ [color, *brush,* paper]
2) bed : sleep :: ______ [paper, *table,* water] [*eating*, rai, book]
3) children : parents :: family ::: students : teachers :: ______ [school, *education*, lesson]
4) tail : fish :: feed : mamals ::: ______ [*movement*, animals, vertebrates] ::::
1. propeller : ship :: wheels : car ::: ______ [vehicles, *transport*, means for transportation, tools]

The participant's task was to chose the correct word among the three alternatives provided for each missing element (in the above, the correct word is printed in italics). As it can be seen, the test consisted of items which varied in difficulty. They involved either concrete or abstract concepts and they had one or two missing words.

The second test addressed the participant's ability to infer a conclusion from two premises based on logical rules. It involved four syllogisms; each of the syllogisms involved two premises and three alternative conclusions (e.g., If the animals live in the cage, then they are not happy. The bird is happy => [the bird lives in the cage; *the bird does not live in the cage*; none of the two]. The participant's task was to choose the right one (here is printed in italics) of the alternative conclusions. The validity of the conclusion must be based solely on true or false logical terms involved in the argument. The syllogisms involved in the test addressed, in two, implication and transitivity; the one of the items was of the decidable type (i.e., conceptually related to the content of the premises) and the other was of the undecidable type (see Efklides, Demetriou, & Metallidou, 1994).

In the quantitative-relational SSS, the first test was the arithmetic operations test used in Study 1. The second test was addressed to proportional reasoning (Demetriou et al., 1993a), specifically, to the ability to grasp and process proportional relations which were systematically complexified. The test involved six items; in three of them the numbers increased (i.e., 6:12 :: 8: ¿, 6:3 :: 8: ¿, 3:9 :: 6: ¿) and in the other three the nymbers decreased (i.e., 3:1 :: 6: ¿, 6:8 :: 9: ¿, 6:4 :: 9: ¿), by a factor of 2, 3, and 1/3, respectively.

The spatial-imaginal SSS was also addressed by two tasks. The first was a version of the classical Piagetian water-level task (Piaget & Inhelder, 1956), which involved two items. That is, a picture of a bottle half-full was presented and the participant's task was to draw the line indicating the water level when the bottle was to be inclined by 45° and 90°, respectively.

The second task was a mental rotation task which involved six items. Participants had to mentally rotate geometrical figures and identify their current position after a 90°, a 180° and a 270° rotation. In each case, a plain figure (e.g., O) and a figure filled with some details (e.g., ∅) had to be rotated.

RESULTS AND DISCUSSION

The data of this study seem appropriate to shed light on (i) the structure of the processing system and (ii) the development of each of the dimensions involved in the processing system across the different symbol systems. The analyses to be presented below are concerned with these issues.

THE STRUCTURE OF THE PROCESSING SYSTEM

In this study the three dimensions of the processing system (namely, processing speed, control of processing, and storage) and three of the SSSs (that is, the verbal-propositional, the quantitative-relational, and the spatial-imaginal) were represented. A first series of analyses aimed to test whether the structure of the processing system and the SSSs involved is the same across the three symbolic systems represented in the study. In other words, these analyses aimed to specify if performance across the different symbol systems and SSSs can be reduced to a common structure or if different structures are required for each of the different systems. Reducing everything to a common structure would strongly indicate that a common processing system exists.

Confirmatory factor analysis was used to answer these questions. According to the theory and previous research (see Study 1), one would predict that common processing mechanisms are applied on all symbol systems. Moreover, the organization of the domain-specific processes and abilities involved in the study would be related in a nested fashion. Thus, a nested factor model which involved seven factors was fitted to the data to test this assumption. In this model (it is presented in Table 2a), the first factor corresponds to the processing speed and it is related to all other variables. Control of processing variables, storage and cognitive measures load additionally on a second factor which represents control of processing. The storage and the cognitive variables loaded additionally on a memory factor; cognitive tasks loaded on a factor representing the general cognitive ability for problem-solving. Moreover, there are three symbol-specific factors to stand for each of the three symbol systems: that is, one factor was prescribed to be related to all verbal variables, another factor to all of the numerical variables, and a third factor to all of the pictorial variables. It was found that the model fit was excellent ($x^2(90)=78.462$, $p=0.80$, $CFI=1.000$).

Table 2: The nested-factor models fitting the greek (a) and the chinese (b) group's performance on tasks assessing speed of processing, control of processing, storage, and the cognitive tasks

(a)

Tasks	Speed of processing	Control of processing	Storage	Cognitive ability	Verbal symbol system	Numeric symbol system	Pictorial symbol system
S(v)	.821*				.302*		
S(n)	.815*					.379*	
S(p)	.930*						-.062
C(v)	.724*	.621*			.299*		
C(n)	.722*	.200*				.461*	
C(p)	.859*	.096					.047

(continued on the next page)

(continued)

(b)

Tasks	Speed of processing	Control of processing	Storage	Cognitive ability	Verbal symbol system	Numeric symbol system	Pictorial symbol system
$M(v_1)$	-.329*	.133	.515*		.032		
$M(v_2)$	-.376*	-.116	.668*		.185		
$M(n_1)$	-.359*	-.168	.497*			-.125	
$M(n_2)$	-.316*	-.086	.581*			-.113	
$M(p_1)$	-.412*	.005	.231*				.618*
$M(p_2)$	-.369*	.029	.307*				.378*
$V\text{-}P_1$	-.147	.077	.276*	.163	.101		
$V\text{-}P_2$	-.288*	.098	.393*	.418*	-.406*		
$Q\text{-}R_1$	-.473*	.005	.378*	.467*		-.077	
$Q\text{-}R_2$	-.442*	.006	.254*	.530*		-.065	
$S\text{-}I_1$	-.423*	.061	.229*	.327*			.190*
$S\text{-}I_2$	-.551*	-.171	.318*	.411*			.309*
S(v)	.981*				.027		
S(n)	.973*					.055	
S(p)	.614*						.019
C(v)	.485*	.197*			.139		
C(n)	.723*	.353*				-.160*	
C(p)	.538*	.481*					.093
$M(v_1)$	-.113	-.089	.519*		.439*		
$M(v_2)$	-.321*	-.037	.408*		.310*		
$M(n_1)$	-.177*	-.202	.650*			.124	
$M(n_2)$	-.141	-.088	.731*			-.038	
$M(p_1)$	-.160	-.300*	.150				.208*
$M(p_2)$	-.207*	-.134	.476*				.844*
$V\text{-}P_1$	-.312*	-.399*	.063	.263*	.031		
$V\text{-}P_2$	-.171*	-.451*	.086	.428*	.253*		
$Q\text{-}R_1$	-.192*	-.142	.201*	.472*		.160	
$Q\text{-}R_2$	-.217*	-.015	.221	.176		.934*	
$S\text{-}I_1$	-.107	-.416*	.213*	.503*			.070
$S\text{-}I_2$	-.135	-.048	.145	.400*			.092

Note: The symbols S, C, and M stand for the speed of processing, control of processing, and short-term memory tasks, respectively. The symbols v, n, and p stand for the symbol systems involved in the tasks, the verbal, the numerical and the pictorial. The numarals 1 and 2 indicate the two trials involved in the short-term memory tasks. The symbols $V\text{-}P_1$, $V\text{-}P_2$, $Q\text{-}R_1$, $Q\text{-}R_2$, $S\text{-}I_1$, and $S\text{-}I_2$ stand for the two tasks addressed to the verbal-propositional, the quantitative-relational, and the spatial-imaginal SSS.

This model suggests that the processing system involves the same dimensions over all symbol systems. This implies that the same processing mechanisms seem to be responsible for the processing and storage of information and for problem-solving in different symbol systems. This conclusion is supported by the fact that a study we conducted in China (see Sample 2) yielded the same result (Zhanq, 1995).

In order to test if the same model can represent performance of the Chinese sample, a multi-sample analysis was run; the model described above was fitted to the data collected from the greek and the chinese sample (the model for each sample is shown in Table 2a and 2b, respectively). The fit of this model, which involved all seven factors, was very good ($x^2(168)=176.870$, $p=0.30$, $CFI=0.995$). Therefore, it is to be concluded that the basic structure of the processing system is the same in the Chinese group as it is in the Greek. That is, it involves the basic processing capacities (speed of processing, control of processing, storage) and the specific domain-related factors, corresponding to the symbol systems addressed by the tasks.

To test the reliability of each of the factors involved in this model, the nested factor method was employed. The model was tested for the two ethnic groups in the same stepwise fashion described in Study 1; the seven factors were added one by one in the model in 7 successive runs to specify whether each one of them contributes significantly to the model fit. As it is shown in Table 3, the first six factors have a significant contribution to the improvement of the model fit. Only the last factor, which represented the pictorial symbol system, was found to be nonsignificant in both groups.

Table 3: Results of tests of the factor-nested models across the greek and the chinese group

	Model Statistics				Change		
Factor included	x^2	df	C.F.I.	p	Äx^2	Ädf	Äp
Speed of processing	358.526	135	.782	.00	----	----	
+ Contol of processing	191.379	120	.930	.00	167.147	15	.005
+ Storage	145.029	108	.964	.01	46.350	12	.005
+ Cognitive ability	128.088	102	.975	.04	16.941	6	.010
+ Verbal symbol system	113.577	96	.983	.11	14.511	6	.025
+ Numerical symb. syst.	94.791	90	.995	.34	18.786	6	.005
+ Pictorial symb.syst	86.260	84	.998	.41	8.531	6	N.S.

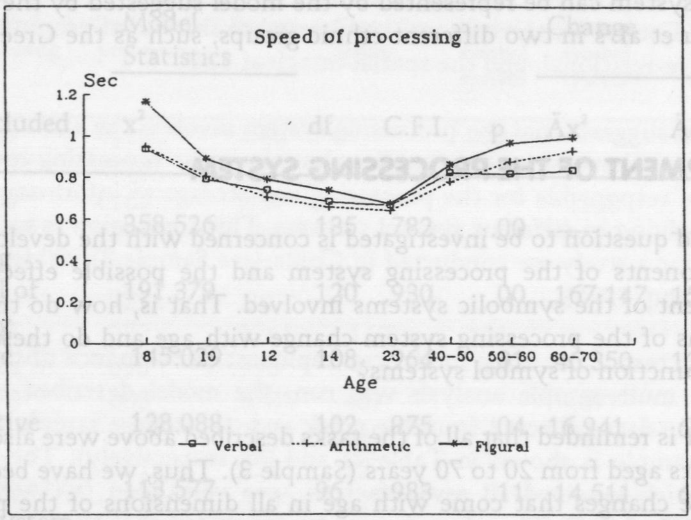
An inspection of the loadings suggests some interesting similarities and differences between the two ethnic groups. Specifically, the first factor is very strong in both groups and, as it was expected, it loads higher on the processing speed measures; this factor represents processing speed. The second factor (processing control) loads high on the control of processing measures in the chinese group; in the greek group it deviates from expectation to some extent because, although it has its higher loadings on two of the three processing control variables, it loads nonsignificantly on the pictorial processing control variable. In the third factor, which was meant to reflect storage, the loadings were similarly loaded on the respective variables in both groups. The forth factor, which represented the general cognitive ability for problem-solving, loaded significanlty on the respective variables, with one exception in both groups. Likewise, the three symbol system factors were closely associated with their corresponding tasks in the two groups. These findings lead to the conclusion that the architecture of the human cognitive system can be represented by the model suggested by the theory of Demetriou et al.'s in two different ethnic groups, such as the Greek and the Chinese.

DEVELOPMENT OF THE PROCESSING SYSTEM

The second question to be investigated is concerned with the development of the components of the processing system and the possible effects on the development of the symbolic systems involved. That is, how do the various dimensions of the processing system change with age and do these changes vary as a function of symbol systems¿

The reader is reminded that all of the tasks described above were also given to participants aged from 20 to 70 years (Sample 3). Thus, we have been able to specify the changes that come with age in all dimensions of the processing system in an age range from 8 to 70 years. Figures 7 shows the development of the speed and the control of processing and storage during this age span. It is obvious that both speed and control of processing improve with increasing age until 20 years, then they stay unchanged until about 35 and after this age they decline. Interestingly, change in control of processing was larger than change in speed of processing. The same pattern as also found to describe the changes in storage (see Figure 8), although changes in this dimension were smaller than changes in the other two dimensions.

Figure 7. Mean response times in the speed of processing and the control of processing measures as a function of age and symbol system.



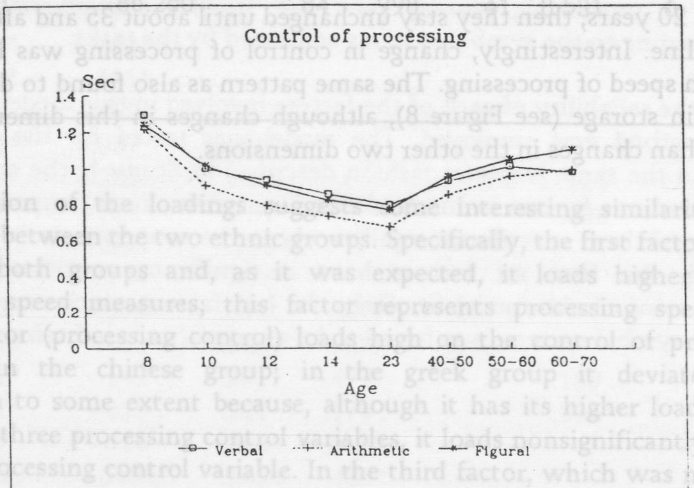
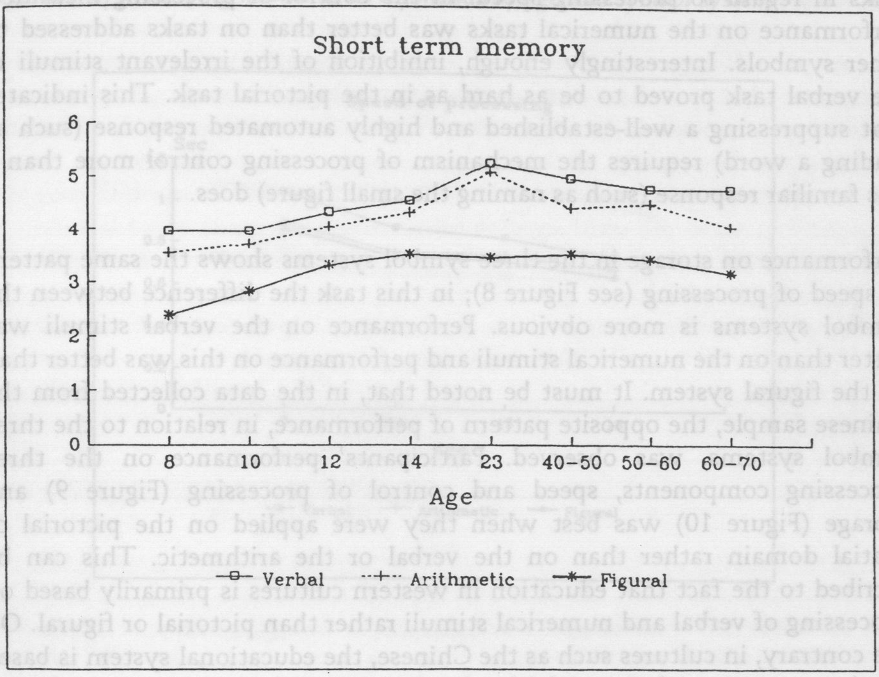


Figure 8. Mean storage scores as a function of age and symbol system.



The reader is reminded that, in the first part of the article, a set of five organizational principles were described. According to our theory, these principles guide the structure and the functioning of the cognitive system in as far as the emergence, organization and development of the SSSs is concerned. Specifically, the principle of developmental variation suggests that the different SSSs may follow partially indepenedent developmental trajectories. Based on this principle, one would assume that the development of different components of an SSS may vary, although to a lesser extend, than components belonging to different SSSs. Such an assumption would be justified on the basis of the fact that the familiarity of the person with different sub-domains or symbol systems connected to a domain can not be identical.

This hypothesis was tested in Study 2 and it was verified. Results showed that performance was not the same in the three tasks addressed to speed and control of processing and storage in the verbal, the numerical and the pictorial domain, respectively. As Figures 7 clearly shows, performance on the figural tasks was lower than performance on the verbal and the numerical tasks in regard to processing speed. In the control of processing measures, performance on the numerical tasks was better than on tasks addressed to other symbols. Interestingly enough, inhibition of the irrelevant stimuli in the verbal task proved to be as hard as in the pictorial task. This indicates that suppressing a well-established and highly automated response (such as reading a word) requires the mechanism of processing control more than a less familiar response (such as naming the small figure) does.

Performance on storage in the three symbol systems shows the same pattern as speed of processing (see Figure 8); in this task the difference between the symbol systems is more obvious. Performance on the verbal stimuli was better than on the numerical stimuli and performance on this was better than on the figural system. It must be noted that, in the data collected from the Chinese sample, the opposite pattern of performance, in relation to the three symbol systems, was observed. Participants' performance on the three processing components, speed and control of processing (Figure 9) and storage (Figure 10) was best when they were applied on the pictorial or spatial domain rather than on the verbal or the arithmetic. This can be ascribed to the fact that education in western cultures is primarily based on processing of verbal and numerical stimuli rather than pictorial or figural. On the contrary, in cultures such as the Chinese, the educational system is based on the processing of pictorial stimuli much more than in western cultures. This is due to the fact that the children are instructed to read and write in the ideographic writing (Biederman & Tsao, 1979; Zhang, 1995).

Figure 9. Mean performance of in the chinese sample on the speed of processing and the control of processing measures as a function of age and symbol system.

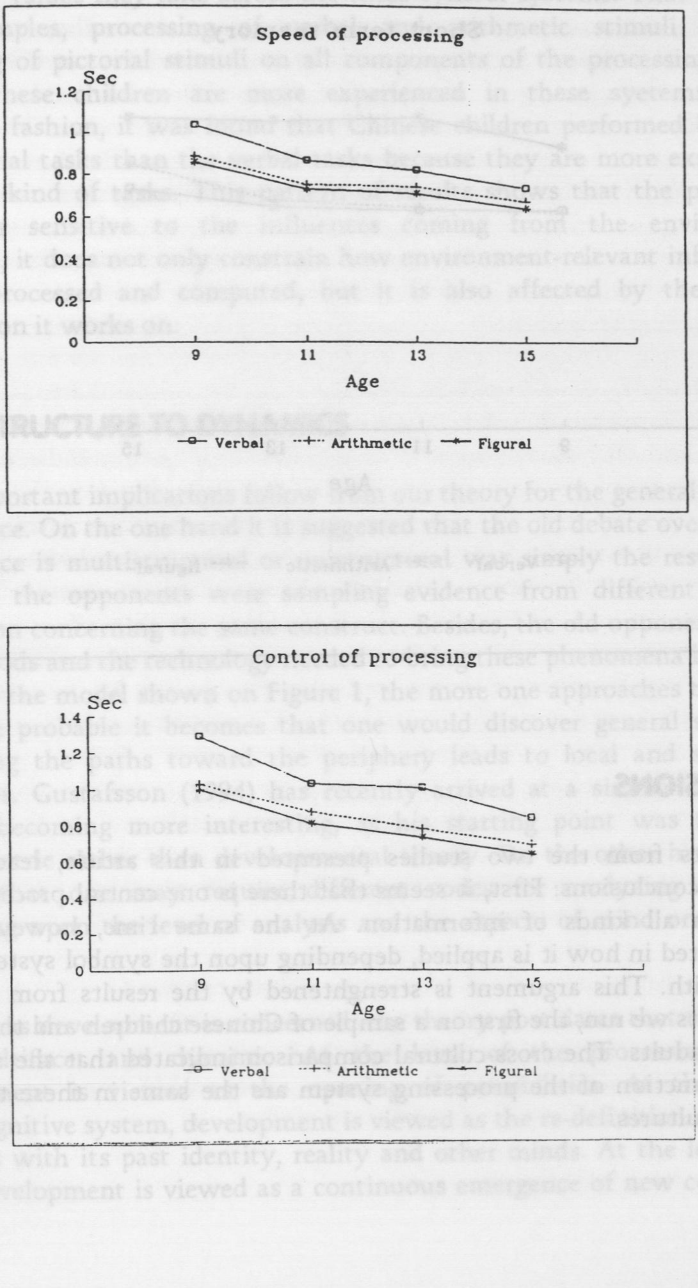
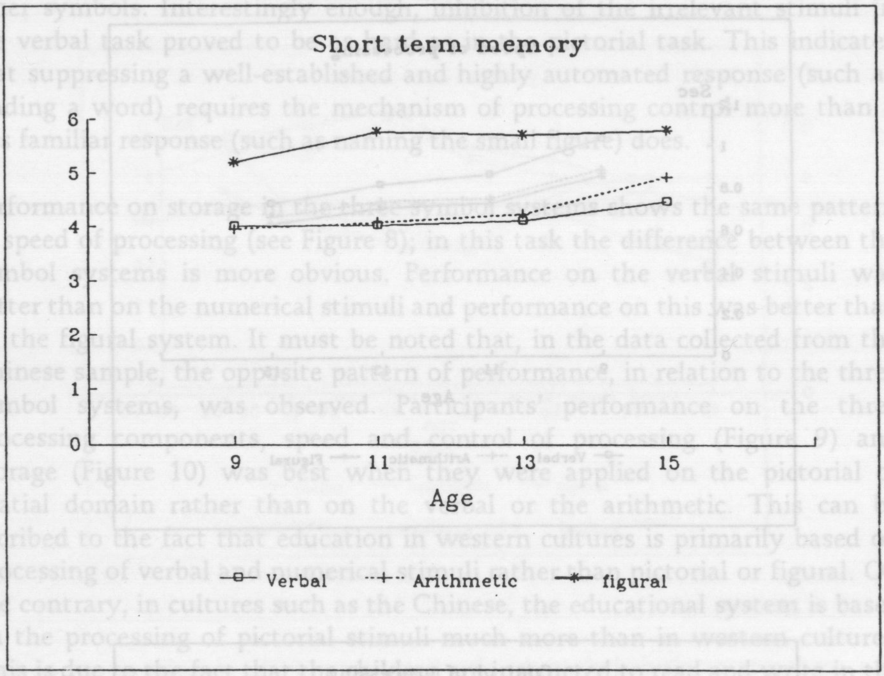


Figure 10. Mean performance of the chinese sample on the storage tasks as a function of age and symbol system.



CONCLUSIONS

The results from the two studies presented in this article, lead to the following conclusions: First, it seems that there is one central processor that applies on all kinds of information. At the same time, however, it is differentiated in how it is applied, depending upon the symbol system it has to deal with. This argument is strenghtened by the results from the two experiments we run, the first on a sample of Chinese children and the second on Greek adults. The cross-cultural comparison indicated that the structure and the function of the processing system are the same in these two very different cultures.

In regard to development, it was found that when the three processing components are applied on various symbol systems, on the one hand, they show a similar rate of development and, on the other, they differ in the «absolute» values they take across the three symbol systems. That is, in the greek samples, processing of verbal and arithmetic stimuli exceeded processing of pictorial stimuli on all components of the processing system because these children are more experienced in these syetems. In an analogous fashion, it was found that Chinese children performed better on the pictorial tasks than the verbal tasks because they are more experienced with this kind of tasks. This pattern of results shows that the processing system is sensitive to the influences coming from the environment. Therefore, it does not only constrain how environment-relevant information will be processed and computed, but it is also affected by the type of information it works on.

FROM STRUCTURE TO DYNAMICS

Some important implications follow from our theory for the general theory of intelligence. On the one hand it is suggested that the old debate over whether intelligence is multistructural or unistructural was simply the result of the fact that the opponents were sampling evidence from different levels of description concerning the same construct. Besides, the old opponents lacked the methods and the technology needed to bring these phenomena in light. In regard to the model shown on Figure 1, the more one approaches the center, the more probable it becomes that one would discover general structures. Traversing the paths toward the periphery leads to local and specialized structures. Gustafsson (1994) has recently arrived at a similar conclusion. This is becoming more interesting, as his starting point was traditional psychometric rather than developmental theory. On the other hand, it also implies that one may require different codes for analyzing the mind depending upon the level of analysis and the aspects of mind one needs to focus on.

In so far as development is concerned, the theory postulates that the mind is also multifacet and dynamic. At the level of the processing system, development is viewed as the opening of possibilities. At the level of hypercognitive system, development is viewed as the re-definition of a mind's relations with its past identity, reality and other minds. At the level of the SSSs, development is viewed as a continuous emergence of new connections between mental units or the modification, deletion, and redistribution of old connections. Developmental changes at the three levels of the cognitive system are interrelated.

Specifically, the theory postulates that developmental causality is a synergic force. It assumes that a change in any of the three levels of the cognitive system is a sufficient cause of changes in any of the other levels. This is so because these systems are functionally tuned to each other. Therefore, a change in any of them, is a disturbance factor which puts the dynamic tuning of the whole system in jeopardy. The direction of change is dictated by the system that has changed first. That is, this system would tend to pull the other systems in the direction toward which it has already moved. A brief description of how synergic developmental causality functions according to the theory may be usefull.

First, a chain of developmental changes may be initiated by a change in processing capacity. Results coming from the longitudinal study on the structure and the development of the processing system indicated that a change in speed of processing is followed in time by a change in the control of processing. It is plausible for one to assume that the faster flow of information that results from an increase in processing speed above a certain threshold makes it more necessary than before to screen incoming information. In turn, an improvement in handling the flow of information in the system makes it able to better exploit its available storage space. Moreover, improvement in storage potential may be felt by the person as an "enlargement in the screen of concience". This may make the person realize that her information handling strategies are not adequate any more. Evidently, this would be a sufficient cause for reorganizations at the level of the hypercognitive system, which would then be reflected on the status of the SSSs. Alternatively, the changes in processing capacity may first lead to the acquisition of a new SSS-specific skill and subsequently affect the status of the hyper-cognitive system.

It is also possible that a chain of changes will be triggered by a change in the hypercognitive system. For instance, the acquisition of a new rehersal or organizational strategy may first affect the handling of the processing system rather than any of the SSSs; or it may first affect an SSS, for instance it may result in an improvement in classificatory ability.

Finally, an improvement in an SSS-specific skill may cause a series of changes in the two general systems. For instance, the practice with arithmetic operations provided by school may lead the child to discover her storage limitations. In turn, this may motivate her to develop strategies that would overcome this limitation. These strategies may, on the one hand, raise the child's self-monitoring and self-regulation facility. On the other hand, they may eventuate in more efficient handling of processing capacity.

In conlusion, the theory presented in this paper is inspired by the assumption that the developing mind can be understood only if the strong points of the developmental, the cognitivist and the psychometric traditions are allowed to converge and become integrated into a comprehensive system. A system that integrates these three traditions should be more succesfull in generating solutions to important practical problems than systems coming from a single tradition, and we expect this approach to be very helpfull in our attempts to answer important but as yet unanswered questions. For instance, we still do not know exactly how each of the various SSSs is activated in the service of the effective functioning of another SSS. Another question refers to the relations between the cognitive and the other systems. A series of projects currently being conducted is systematically directed at the pursuit of answers to these questions.

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