Available online at www.sciencedirect.com
ScienceDirect
Intelligence 36 (2008) 437–454
INTELLIGENCE

Modelling the structure and development of *g*

Andreas Demetriou *, Antigoni Mouyi, George Spanoudis

University of Cyprus, Cyprus

Received 31 March 2007; received in revised form 29 September 2007; accepted 5 October 2007
Available online 19 November 2007

Abstract

This study investigated the structure and development of processes involved in *g*. One hundred and forty children, about equally drawn among primary school grades 1–6 were examined by four types of Stroop-like speeded tasks addressed to processes of increasing complexity (i.e., speed of processing, perceptual discrimination, perceptual control, and conceptual control) and tasks addressed to working memory, information integration, and reasoning. Structural equation modelling showed that these processes are hierarchically organized so that the processes at each subsequent higher level in the hierarchy include the processes of all previous levels together with processes specific to this level. Speed of processing and perceptual control were the most powerful predictors of the state of processes residing higher in the cascade. Analysis of variance showed that all of these processes improve systematically with age and that developmental differences in higher level processes are partly accounted for by lower level processes and by factors germane to themselves. The implications of these findings for the general theory of intelligence are discussed.

Keywords: Control of processing; Development; General intelligence; Information integration; Reasoning; Speed of processing; Working memory

1. Introduction

General intelligence, or *g*, is a very powerful and well established construct in psychology. In psychometric theories of intelligence *g* is a higher-order construct that emerges from a matrix of correlations between diverse cognitive tests as a result of the so-called "positive manifold". That is, it reflects the fact that all tests are positively correlated (Carroll, 1993; Detterman, 2002; Humphreys & Stark, 2002; Jensen, 1998, 2002). The more diverse the tests included in a battery, in terms of the abilities addressed, the stronger is the *g*-factor emerging from it (Humphreys & Stark, 2002). This statistical construct is supposed to reflect the operation of common processes which constrains performance on all of the tests and is responsible for the positive manifold (Demetriou, 2002; Detterman, 2002).

Recent neuroscience and genetic research investigates the underlying brain (Garlick, 2002; Jung & Haier, in press) and genetic mechanisms (Kovas & Plomin, 2006; Posner, Rothbart, & Sheese, 2007; Posthuma & de Geus, 2006) that may be associated with *g*. Further progress in our understanding of the nature, functioning, development, and training of intelligence will come from an integrated neuro-cognitive theory of

---

* Corresponding author. Department of Psychology, University of Cyprus, P.O. Box 537, 1678 Nicosia, Cyprus. Tel.: +35722892080; fax: +35722892071.

E-mail address: ademetriou@ucy.ac.cy (A. Demetriou).

0160-2896/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.intell.2007.10.002

intelligence that would specify how different cognitive processes underlying *g* are served by specific networks or patterns of neuronal or neurotransmitter activity and functioning (Demetriou, 2006; Demetriou & Mouyi, in press; Demetriou, Spanoudis, & Mouyi, in press). A prerequisite for this integrated neuro-cognitive theory is an adequate cognitive theory of *g* that would be able first to direct the study of the brain and then be integrated with it. This theory is not yet available because our knowledge of the processes involved in *g* and their relations is far from complete (Detterman, 2002). The present study is a contribution to the development of this theory. Specifically, this study was designed to empirically identify the basic processes involved in *g* and specify their structural and developmental relations.

Spearman (1927) defined *g* in terms of the inferential processes involved in understanding and problem solving, namely eduction of relations and correlates. These two noegenetic laws "require inductive and deductive reasoning, grasping relationships, inferring rules, generalizing, seeing the similarity in things that differ (…) or the difference between things that are similar (…), problem solving, decontextualizing a problem (…)" (Jensen, 1998, pp. 35–36). As is common in science, since that time, research progressed in a reductionist manner. Researchers attempted to explain the functioning of the inferential components of *g* in terms of more basic processes of processing efficiency and capacity, such as speed of processing, efficiency of inhibition, working memory, and executive control and planning. There is general agreement that *g* is related to all of them and that they are themselves interrelated. However, this is as far as agreement goes. That is, there is conflicting evidence about the precise relation of each to *g* and about their interrelations. As a result, different authors stress the importance of different processes. Some researchers stressed the importance of speed of processing (Demetriou, Christou, Spanoudis, & Platsidou, 2002; Demetriou, Zhang, Spanoudis, Christou, Kyriakides, & Platsidou, 2005; Hunt, 1980; Jensen, 1998; Kail, 1991; Kail & Salthouse, 1994). Others maintained that control and selective attention processes are more important than speed (Dempster, 1991; Embrertson, 1995; Stankov & Roberts, 1997). Other researchers maintained that working memory is the crucial capacity component of *g* (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990; Miller & Vernon, 1996). Finally, some researchers stress the importance of executive control and planning (Naglieri & Das, 2002; Zelazo & Frye, 1998).

We suggest that this inconsistency in findings results from the lack of a clear model of the possible interrelations between these processes. Formulating this model would allow the operationalization of the various processes by tasks specifically addressed to each of them. This, in turn, would allow the a priori testing of the reductionist model that more complex processes can be partly reduced to simpler processes. In a nutshell, this reductionist model assumes that simpler processes are embedded in more complex processes so that the processes at each subsequent higher level in the hierarchy include the processes of all previous levels together with processes specific to this level.

In the present study, we designed tasks addressed to the following processes: speed of processing (SP), perceptual discrimination (PD), perceptual control (PC), conceptual control (CC), working memory (WM), information integration (InfI), and reasoning (Reason). We hope to show in Method that the tasks addressed to these processes conform to Sternberg's (1969) additive factor method in the fashion summarized in the Eqs. (1)–(6) shown below:

$$\mathrm{PD} = \mathrm{Speed} + \text{discrimination processes}; \tag{1}$$

$$\mathrm{PC} = \mathrm{Speed} + \mathrm{PD} + \text{control of interference between perceptual attributes}; \tag{2}$$

$$\mathrm{CC} = \mathrm{Speed} + \mathrm{PD} + \mathrm{PC} + \text{control of interference from perceptual attributes to knowledge in long} - \text{term memory}; \tag{3}$$

$$\mathrm{WM} = \mathrm{Speed} + \mathrm{PD} + \mathrm{PC} + \mathrm{CC} + \text{storage and retrieval processes}; \tag{4}$$

$$\mathrm{InfI} = \mathrm{Speed} + \mathrm{PD} + \mathrm{PC} + \mathrm{CC} + \mathrm{WM} + \text{planning and integration processes}; \tag{5}$$

$$\mathrm{Reason} = \mathrm{Speed} + \mathrm{PD} + \mathrm{PC} + \mathrm{CC} + \mathrm{WM} + \mathrm{InfI} + \text{inferential processes}. \tag{6}$$

Attention is drawn to the hypothesis that these processes are organized in three main levels: speed, which constrains all other processes residing higher, control (PD, PC, and CC), and representational processes (WM, InfI, and *R*). Moreover, we hoped to show that the cascade of relations runs through these three main levels so that perceptual discrimination reflects sheer speed of processing together with the processes required to discriminate between two simple stimuli and identify the target one. Perceptual control reflects the processes involved in perceptual discrimination and also the processes required for the control of the interference of the strong but irrelevant dimension of the stimulus condition in the identification of the weaker but relevant dimension. Conceptual control reflects all of the processes included in perceptual control and also the processes required to control interference from perceptual attributes to knowledge in long-term memory. Working memory involves all of the processes above and also the processes required to store and recall information. Information integration involves all of the processes above and also the processes required to execute an action plan for the identification and integration of information as specified by the task requirements. Finally, reasoning involves all of the processes above and also the inferential processes required to go beyond the information given in order to draw the relevant logically sound conclusions. Therefore, the main structural concern of this study is to examine, by means of structural equations modelling, (1) if this general pattern of relations is empirically sound and (2) to specify the exact magnitude of each of the various relations in each of the equations.

In concern to development, three main predictions can be tested. First, performance is expected to improve across all four types of measures with age in the age span of 6 to 12 years covered by the study. That is, reaction times to the speeded performance tasks should decrease with age, working memory should increase, information integration must be able to deal with increasingly complex patterns of information, and reasoning should become able to deal with increasingly more complex and more abstract problems. Second, based on the structural relations specified above, it is anticipated that part of the differences between age groups in regards to a particular process, such as, for example, reasoning, must be significantly associated to differences in the processes residing lower in the hierarchy, such as processing efficiency and working memory. However, third, a significant part of changes in representational and reasoning processes with age is expected to be germane to these processes per se.

2. Method

2.1. Participants

A total of 140 participants were tested, all of them coming from middle class families living in Nicosia, a city of about 250,000 citizens which is the capital of Cyprus. These participants were about evenly distributed across the six primary school grades and gender. Specifically, from first through sixth grade, there were 23 (11 female, 12 male; mean age 80.3 months, SD=3.7), 24 (12 female, 12 male; mean age 92.6 months, SD=3.5), 22 (12 female, 10 male; mean age 106.2 months, SD=4.9), 21 (11 female, 10 male; mean age 117.9 months, SD=3.4), 25 (13 female, 12 male; mean age 128.3 months, SD=3.2), and 25 (13 female, 12 male; mean age 140.4 months, SD=3.7) participants, respectively.

2.2. Tasks

2.2.1. Processing efficiency

The tasks addressed to the four dimensions of processing efficiency were as follows.

2.2.1.1. Speed of processing. A simple choice reaction time task was used to address speed of processing. Specifically, a computerized version of a part of the Simon effect task was used that does not involve any kind of conflict management between stimuli and responses. Children were instructed to press the M key (which is on the far right end of the keyboard) when the target stimulus (a number digit) appeared on the right half of the screen and the Z key (which is on the far left end of the keyboard) when the stimulus appeared on the left half. Reaction times between stimulus and response onset were recorded. Twenty trials were presented for each condition and their average was automatically calculated. Thus, there were two measures of speed of processing.

A filter set at 300 and 1000 ms was used to exclude unreasonably fast or slow responses, respectively. Wrong responses were also automatically excluded. The same exclusion criteria were used for the speeded performance tasks to be described below. Moreover, the filter for unreasonably slow responses for the perceptual and the conceptual control tasks to be described below was set at 5000 ms.

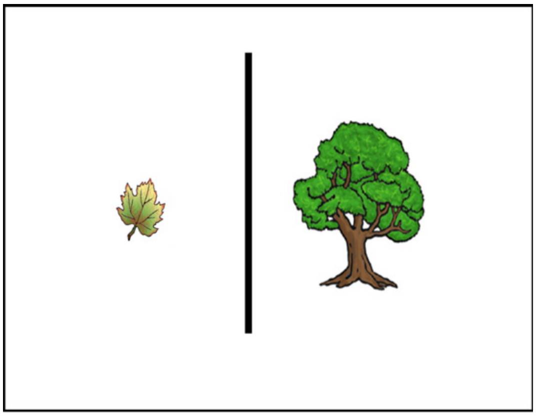


Fig. 1. Examples of tasks addressed to perceptual discrimination (specify the bigger object on the screen).

2.2.1.2. Perceptual discrimination. To examine perceptual discrimination, two pictures, one small and one big, were presented simultaneously on the screen, one on the left and the other on the right half of the screen (Fig. 1). The position of the two pictures alternated randomly between the two sides of the screen and the participants were asked to choose the bigger of the two by pressing the M or the Z key, as described above. The objects in each pair of pictures were related physically (e.g., a "leaf" and a "tree", see Fig. 1), functionally (e.g., a "hammer" and a "nail"), and conceptually (e.g., an "apple" and a "cherry"). Thus, there were three measures of perceptual discrimination, each involving 8 trials.

2.2.1.3. Perceptual control. A series of Stroop-like tasks were used to address perceptual control. Specifically, there were tasks using verbal, numerical, and figural stimuli. The verbal tasks were similar to the standard Stroop (1935) task, as shown in Fig. 2A. That is, three Greek words, which have the same number of letters – κόκκινο (red), πράσινο (green), κίτρινο (yellow) – were used and participants were tested under two combinations of meaning and ink-color, that is, word reading-compatible color and color naming-incompatible word, which is considered to be the proper test for perceptual control. Participants were instructed to use the R, the G, and the Y keys for red, green, and yellow, respectively. To facilitate responding, a red, a green, and a yellow sticker were placed on the respective keys.

The number and the figural tasks were organized according to Navon (1977). Specifically, the number task involved the digits 4, 7, and 9, composed either of the same digit (compatible condition) or a different digit (incompatible condition), as shown in Fig. 2B. That is, in the compatible condition, the large digit (e.g., 7) was composed of the same "small" digit (i.e., 7). In the incompatible condition, the large digit (e.g., 7) was composed of one of the other digits (e.g., 4). The participants were tested under two combinations of the dimension to be attended to and compatibility, that is, large-compatible and small-incompatible. Only the last condition is a proper test of perceptual control. Reaction times on this condition were taken as the perceptual control indicators. Number keys on the keyboard were specified as response keys for the numbers used.

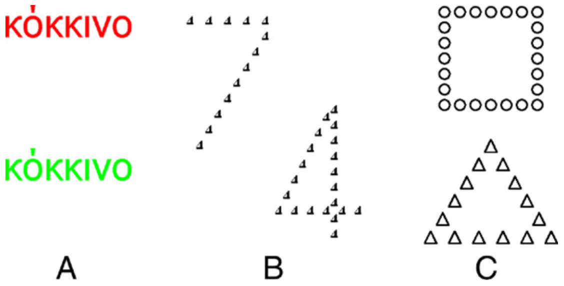


Fig. 2. Examples of Stroop-like tasks addressed to verbal (A), numerical (B) and figural (C) information. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

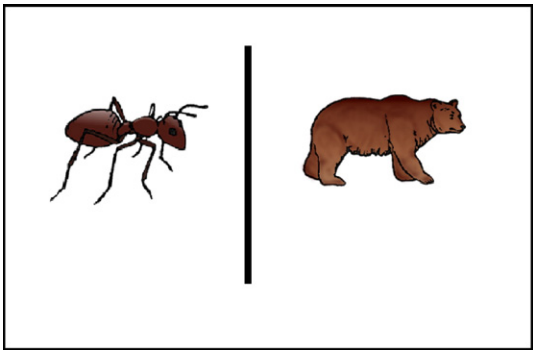


Fig. 3. Example of tasks addressed to conceptual control (specify the bigger object in reality).

The figural system was addressed through a task battery similar to the number battery. That is, three geometrical figures (circle, triangle, and square) were used to produce the two combinations of the dimension to be attended to and compatibility, as shown in Fig. 2C. The participants were instructed to use the S, the C, and the F keys for "square", "circle", "triangle", respectively. In order to facilitate participants, stickers showing a square, a circle, and a triangle were placed on the respective keys. Thus, there were three measures of perceptual control, one for each symbol system. Each measure involved 9 trials.

2.2.1.4. Conceptual control. The tasks addressed to conceptual control were similar to the perceptual discrimination tasks. That is, pairs of objects, one small and one big, were presented on the left and the right half of the screen in a way that the size of the two pictures would not differ. (Fig. 3). The participant's task was to choose the object which was bigger in reality. Therefore, the participant would have to control the interference coming from the object that seemed bigger on screen, but it was smaller in reality, since the picture of the smaller object was enlarged so that the two objects would be presented as equal in size. These tasks are similar to those used by Paivio (1975) to examine control processes when manipulating mental images.

The M and the Z keys were used as response keys for the two sides of the screen. The pictures in each pair were related physically (e.g., a "sail" and a "boat"), functionally (e.g., a "knob" and a "door"), and conceptually (e.g., an "ant" and a "bear", see Fig. 3). Thus, there were three measures of conceptual control, each involving 8 trials.

Cronbach's alpha for the set of 11 measures (two for speed, three for perceptual discrimination, three for perceptual control, and three for conceptual control) described above was very high (.89). Cronbach's alpha varied between .87 and .90, if any one of these 11 measures was deleted, indicating that all of these measures were very reliable indicators of processing efficiency.

It should be noted that wrong responses were rare. Specifically 5.5%, 6.6%, 5%, and 23.6% of the responses given to the speed, the perceptual discrimination, the perceptual control, and the conceptual control tasks, respectively, were wrong. Moreover, wrong responses were not related to reaction times on all but one of these tasks. The mean error rate-reaction time correlation was −.10 and it ranged from −.44 (color recognition in perceptual control) to −.02 (figure recognition in perceptual control). However, the error rate tended to be negatively related to age. The mean age-error rate correlation was −.15 and it ranged from −.30 on one of the speed measures to .00 on one of the perceptual control measures.

2.2.2. Working memory

Four working memory tasks addressed visuo-spatial and numerical storage. Unfortunately it was not possible to use any other working memory tasks in this study, such as tasks addressed to verbal working memory, because, in general, working memory tasks are time-demanding. Adding more tasks would exceed the time available for the experiment.

2.2.2.1. Visuo-spatial working memory. In the first of the tasks addressed to visuo-spatial memory, a total of eight arrangements of geometrical figures of varying complexity were presented to the participants. Specifically, of this total, two arrangements involved two figures, two arrangements involved three figures, and the other four arrangements involved four, five, six and seven figures, respectively. Each of the arrangements was presented for as many seconds as the number of figures in it. Four alternative arrangements, each one corresponding to one of the numbers 1–4, were presented immediately after the presentation of the target arrangement. The participant's task was to identify the target arrangement among four alternative arrangements, presented immediately after the presentation of the target arrangement.

In the second task, the component figures were superimposed on each other. Specifically, triangles, squares, rectangles, hexagons, circles, open angles, and arcs, were used to form configurations of increasing complexity. A total of 15 stimulus arrangements were presented, organized in five levels of difficulty. Specifically, task difficulty varied in relation to the number of component figures superimposed on each other to form the target configuration. Thus, there were five difficulty levels, each including three tasks. The participant's task was to identify the stimulus arrangement among five alternatives presented immediately after the presentation of the stimulus arrangement.

2.2.2.2. Numerical working memory. These tasks were patterned on Case's (1985) task addressed to working memory. Both tasks involved seven levels of difficulty. Each level was defined by the number of items to be stored in memory, so that the participant would be able to make a simple mathematical comparison. In the first task, in each level, a set of numbers digits, differently colored, were presented in succession for 2s each. At the end of the presentation of each set, a target digit was presented and the participant's task was to specify if this target digit was bigger than the same color digit included in the set. Four trials were given for each level of difficulty. Participants ought to succeed in at least two of the four trials in order to move on to the next level. The second task was identical to the first in all respects but the presentation of the numerical information involved in each trial. That is, instead of number digits, the numbers were represented by dots of equal size. Participants were instructed to keep in memory both the numerical information and the color of the items presented in each trial.

Participants were scored for their performance on each of these four tasks. Specifically, the score given to each task was equal to the highest difficulty level attained. Following Case (1985), participants were credited with a level if they succeeded on half or more of the items addressed to this level. Participants missing a level Ln, that is, participants succeeding on level Ln-1 and level Ln+1, were credited with level Ln. The maximum score was 5 for the visuo-spatial tasks and 7 for the numerical tasks.

Cronbach's alpha for the four working memory tasks was satisfactory (.57), taking into account their small number. Cronbach's alpha varied between .48 and .52, if any one of these 4 measures was deleted, indicating that all of these measures were satisfactory indicators of working memory.

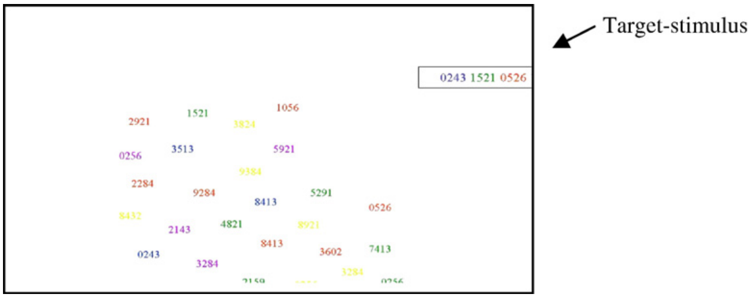


Fig. 4. Item addressed to information integration. Note: Participants must specify if all components of the target stimulus are present on the screen.

2.2.3. Information integration

In this task a target stimulus was presented in the top right corner of the screen as shown in Fig. 4).

There were three kinds of stimuli: words, number digits, and pictures of objects. The components of the target stimulus (i.e., syllables for words, numbers for the number digits, and shapes for the pictures of objects), together with other irrelevant but similar components, were scrambled on the rest of the screen. Participants were asked to decide if all of the components of the target stimulus were present on the screen (by pressing the respective key standing for "yes" or "no"). The complexity of the items varied in relation to the number of components involved in the target stimulus and the number of redundant information on screen. Obviously, in order to succeed on this task participants would have to be able to keep the necessary information in working memory, at least in part, formulate and execute a search plan for identifying components, control interference from irrelevant components, integrate the results of research into an integrated representation which could be mapped onto and compared with the target stimulus. Thus, there were three measures of information integration, one for each symbol system. A filter for unreasonably slow responses for these tasks was set at 30,000 ms.

Cronbach's alpha for the three information integration tasks was satisfactory (.63). Cronbach's alpha varied between .40 and.63, if any one of these 3 measures was deleted, indicating that they were satisfactory indicators of information integration.

2.2.4. Reasoning

A long battery of tasks addressed inductive and deductive reasoning. Both types of reasoning were addressed through tasks involving verbal, mathematical, and spatial relations.

2.2.4.1. Inductive reasoning. Two types of verbal inductive tasks were used: syllogistic and analogical.

2.2.4.2. Verbal syllogisms. All of the syllogistic tasks were based on a story where three members of a class were first named (Pi, Xi, and Yi are Chinese), and a general statement about an action of all members of the class (They ride a bicycle) and three statements describing the same food preference of each (Pi likes to eat rice, Xi likes to eat rice, Yi likes to eat rice) were given. Based on this story, five tasks were presented asking the participant to make an induction about food preferences or actions based the information provided (e.g., Tsi is a Chinese; does he like to eat rice?). There were also two general questions probing the participant's about the open nature of inductive reasoning (e.g., Is it possible to have a Chinese who doesn't like to eat rice?). Participants were asked to answer all of the five items by choosing one of three alternatives: "certainly yes", "certainly no", "may be yes may be no". A point was given for each right choice. Difficulty was controlled in reference to the relations between the class or action specified in the story and the new case referred to in the problem.

2.2.4.3. Verbal analogies. Seven analogies of the a:b::c:d type were given, where one of the four components was missing (components b and c were missing in two cases and component d was missing in three cases). Participants were asked to choose the right answer among four alternatives. One point was given for each right answer. Difficulty was controlled in reference to the familiarity and abstractness of the relations involved.

2.2.4.4. Mathematical syllogisms. Seven tasks addressed inductive syllogism in mathematical reasoning. All of these tasks were based on the understanding of the relations between even and odd numbers. Specifically, four items were based on a drawing where the numbers 1–7 were drawn on a number line. The numbers 1, 3, 5, and 7, were drawn white and numbers 2, 4, and 6 were drawn black. Beneath each of the numbers there was a dot array of as many dots as the number. The dots were arranged in pairs so that there was an extra non-paired dot for each of the odd numbers. The arrays for the odd (white) numbers where also white and the arrays for the even (black) numbers were also black. Based on this arrangement, there were four problems concerning the understanding of the relations between odd and even numbers. For example, one of these problems stated that 8 is not a white number and the participant was asked to specify if, when drawn like the other numbers, there will be an extra dot in the dot array associated with it. There was another set of three problems concerned with the relations between prime, odd, and even numbers. The relation was first stated, examples of the relation were given, and then the participant was asked to induce the condition of another number. For example, it was stated that prime numbers are those divided by 1 and themselves and that the numbers 2, 3, 5, 7, 11, and 13 are prime numbers. Then it was stated that number 4 is an even number and it can be expressed as the sum of two prime numbers ($2+2=4$), number 6 is an even number and it can be expressed as the sum of two prime numbers ($3+3=6$), and number 8 is an even number and it can be expressed as the sum of two prime numbers ($5+3=8$). Participants were asked to judge if number 20 which is an even number can be expressed as the sum of two prime numbers.

2.2.4.5. Mathematical analogies. Six mathematical analogies were presented. Numbers in each of them were presented in two columns of three full pairs. The number on the right of the fourth pair was missing. The participant's task was to specify the missing number. The six analogies involved the following relations:2χ, 3χ, χ^3, $2\chi+1$, $\frac{\chi}{2}-1$, χ^2-1.

2.2.4.6. Spatial syllogisms. Six tasks addressed the ability to extract a general rule underlying movement in a spatial arrangement and apply this rule in a similar but new context. Specifically, small black and white circles were ordered in an

$m \times n$ orthogonal matrix like the one shown in Fig. 4. The matrix was supposed to represent a garden, where dots stood for stones. According to the story, worms moved in the garden according to a rule related to the color of the stones (i.e., they turn around each black dot if it was alone and move forward until they meet the next single black dot). The course of the two worms was drawn and participants were asked to draw the course of a third one. Complexity varied as a function of the size of the matrix (there were two 5×5, two 7×7, and two 11×11 matrices) and the number of turns in the matrix (Fig. 5).

2.2.4.7. Spatial analogies. Seven a:b::c:d Raven-like matrices addressed spatial analogical reasoning. All matrices involved a pair of geometrical figures connected by a certain rule and the participant's task was to identify this rule in the relation between the components of the a:b pair and apply it on the c component of the second pair in order to select the missing d component among four alternatives. Complexity varied as a function of the dimensions involved (color, shape, and transformation).

2.2.4.8. Deductive reasoning. Deductive reasoning was addressed by verbal, mathematical, and spatial syllogisms.

2.2.4.9. Verbal syllogisms. Sixteen standard arguments addressed propositional reasoning. All of these arguments involved two premises and a conclusion and the participant's task was to indicate if the conclusion is right, wrong, or undecidable. To minimize possible effects of prior knowledge or familiarity, the information in all of the arguments was unfamiliar to the participants. That is, all of the arguments were concerned with life on imaginary planets such as the example following: If a Paff has a square head then she lives on the red planet. Psi has a square head. Conclusion: Psi lives on the red planet.

Difficulty was controlled in reference to the type of the logical relations involved. That is, these arguments addressed modus ponens (i.e., if p then q, p, therefore q; 4 items), modus tolens (i.e., if p then q, not q, therefore not p; 4 items), the fallacy of affirming the consequent (i.e., if p then q, q, therefore no logically correct conclusion can be reached; 4 items), and the fallacy of denying the antecedent (i.e., if p then q, not p, therefore no logically correct conclusion can be reached; 4 items). It is known that some logical relations (e.g. modus ponens) are more easily constructed than other relations (e.g., modus tolens). Moreover, it is known that invalid or fallacious arguments are more difficult than valid arguments because the invalid arguments require one to understand that propositions do not constrain each other. Finally, negative premises impose extra load on an argument because they require one to transform the premises before integrating them for the sake of the argument.

2.2.4.10. Mathematical syllogisms. Seven tasks addressed deductive reasoning involving mathematical relations. Participants were asked to specify the number digits (0–9) to be placed in three or four boxes, drawn side by side, based on a set of propositions constraining each other. For example, the propositions in one of the problems were as follows: (1) The third digit is 1. (2) If the third digit is the smallest of all three, then the first digit is 4. (3) There is no 0. (4) The second digit is either the smallest or the largest digit that we can write. (5) Each digit appears only once.

Difficulty was controlled in reference to the number of digits to be specified (four problems involved three and three problems involved four digits), the number of propositions involved (three 3-digit problems involved five propositions and one involved six propositions; of the 4-digit problems one involved seven, one involved eight, and one involved nine propositions), and the logical relations involved in the propositions.

2.2.4.11. Spatial syllogisms. Finally, seven tasks addressed deductive reasoning involving spatial relations. The structure of these tasks was similar to the structure of the tasks above involving mathematical relations. That is, participants were asked to specify the position of a number of animals or persons sitting next to each other based on the information of a number of propositions constraining each other in the fashion of the mathematical reasoning tasks described above. Tasks involving three, four, five, six, seven, and eight persons were involved. Two, three, four, five, and eight propositions were involved. One of the tasks was as follows: "A train with 3 coaches carries the following three animals to the zoo: an elephant, a lion, and a bear. No two animals can be in the same coach. Your task is to specify the coach of each animal based on the following propositions. If the lion is in the second coach, then the elephant is in the third one. The lion's coach is neither the first nor the third". A diagram was provided for all seven tasks where the participants marked their answers. One point was given when all names were correctly placed on the diagram.

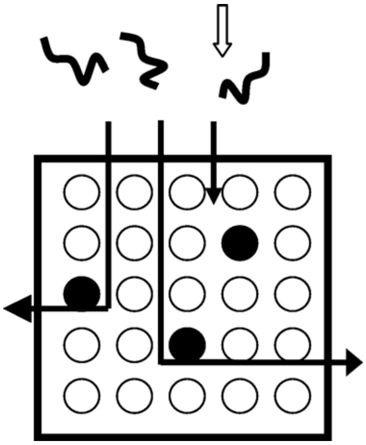


Fig. 5. Example of spatial syllogism tasks.

Cronbach's alpha for the set of 9 measures described above (i.e., six inductive and three deductive reasoning measures) was very high (.81). Cronbach's alpha varied between .79 and .80, if any one of these 9 measures was deleted, indicating that all of these measures were very reliable indicators of reasoning. The reliability of each of the two scales was also very high (i.e., .78 and .76 for inductive and deductive reasoning, respectively).

Two composite scores were formed based on the nine observed variables used in the reasoning test. Specifically, the score for inductive reasoning was the mean score of the six inductive reasoning tests and the score for deductive reasoning was the mean score of the three deductive reasoning tests.

2.3. Procedure

Testing took place at the school premises in two sessions. The reasoning test was administered first followed by the processing efficiency, the information integration, and the working memory tests. The presentation order of tasks was counterbalanced within each session.

The reasoning battery was a paper-and-pencil test. Eight-year-old or older participants were given an example, written on the whiteboard, and the relevant instructions for every type of tasks and they were asked to complete the test on their own, and ask for further clarifications if needed. Six- and 7-year-olds were let to complete the test in a step-by-step fashion. Specifically, tasks were completed one by one, after all of the children in the classroom completed their work on the current task. Demonstration and explanations were given before working on each task. This differentiation in testing procedures between the two younger age groups and older children was considered necessary to compensate for limitations in the attention span and testing experience of younger children compared to the older ones.

All of the second session tests were developed within the e-prime environment and they were computer administered. Testing took place in groups of 12 children, each sitting in front of a personal computer especially prepared for the experiment. Participants were introduced to the tests by one of the authors. The requirements of each test were explicated and an example was demonstrated on the whiteboard. Clarifications were given as needed. Every test began with a practice session aiming to familiarize and train the children how to work on it. No child failed this session. Testing conditions were the same for all age groups.

3. Results

3.1. Structural relations between processes

To test the hypothesis about the structural relations between the various processes addressed by our study, a series of structural equation models were evaluated. The statistics of the variables used in all of the analyses to be presented below are shown in Table A1 in Appendix A. The correlation matrix for these variables is shown in Table A2 in Appendix A. It can be seen that means based on raw scores representing performance on all tasks were used in the various analyses. These models implement our hypotheses specified by Eqs. (1)–(6) that the processes tested here are hierarchically organized, first, in three main levels (i.e., speed, control, and representational processes) and, second, across these three main levels so that each process includes all processes residing lower together with processes specific to this level. In the present case, the various processes were represented by seven first-order factors. Specifically, speed of processing (SP), perceptual discrimination (PD), perceptual control (PC), conceptual control (CC), working memory (WM), information integration (InfI), and reasoning (*R*) were identified by relating each of the corresponding sets of measures to a separate factor (see Method). The simplest and most direct test of the hierarchical relations between factors suggested by Eqs. (1)–(6) would be a simplex model (Gustafsson & Carlstedt, 2006) where each factor in the hierarchy is regressed on the factor residing one level lower in the fashion shown in Fig. 6A. The fit of this model was very good, χ^2 (146) = 178.713, p = .033, CFI = .965,

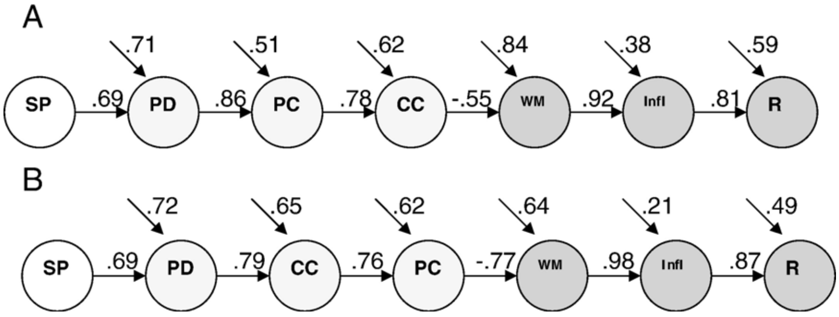


Fig. 6. The simplex model of the hierarchical relations between factors. Note: SP: speed; PD: perceptual discrimination; PC: perceptual control; CC: conceptual control; WM: working memory; InfI: information integration; *R*: reasoning.

RMSEA = .053 (90% confidence interval for RMSEA = .016 – .077).

However, one might argue that the hierarchical order of factors suggested by the model above is arbitrary and that a large number of alternative models might fit equally well. If sound, this argument would undermine our assumptions about the hierarchical integration of processes advanced here. To test this argument, a series of alternative models were tested. These models are summarized in Table 1. Specifically, first, the relations between factors in the simplex model were completely reversed. That is, the cascade of factors was specified as follows: *R* → Infl → WM → CC → PC → PD → SP. Obviously, this is a test of the extreme objection that even a model dramatically different from the hypothesized model would fit the data. The fit of this model was very poor, χ^2 (146) = 422.748, p = .000, CFI = .701, RMSEA = .153 (90% confidence interval for RMSEA = .135–.169).

In a second model, the cascade order of the factors from simple to complex was preserved within each of the three levels of factors standing for processing efficiency and representational processes. However, the relation between the levels was reversed so that the representational level was taken as the basic level relative to speed and control. That is, the cascade was specified as follows: [WM → Infl → *R*] → [SP] → PD → PC → CC]. Obviously, this model tests the assumption that the main levels of the mental architecture are related in a top-down fashion, from representational to efficiency and control processes, although the processes are hierarchically organized within each of them. The fit of this model was again very poor, χ^2 (146) = 422.748, p = .000, CFI = .701, RMSEA = .153 (90% confidence interval for RMSEA = .135–.169).

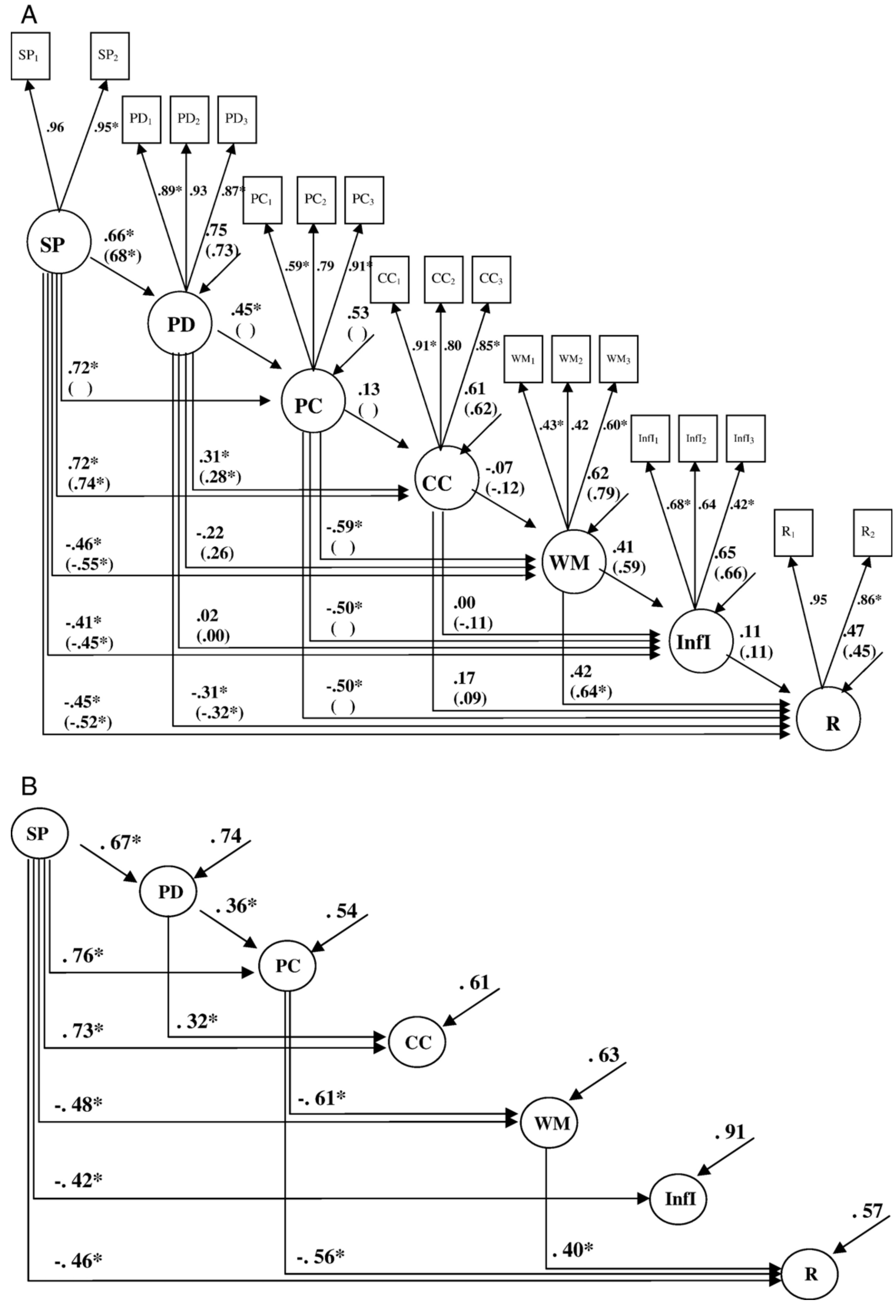
In the third model all of the factors but WM retained their position as specified in the original simplex model. Specifically, in this model, working memory was taken as the fundamental factor initiating the cascade. Specifically, the cascade was specified as follows: WM → SP → PD → PC → CC → Infl → *R*. This model tests the assumption espoused by several scholars that working memory is the pivotal factor in the organization of intelligence (Kyllonen & Christal, 1990). The fit of this model was poor, χ^2 (146) = 268.712, p = .000, CFI = .868, RMSEA = .102 (90% confidence interval for RMSEA = .082–.120). In another set of models, one of the three factors involving some kind of control was allowed to initiate the cascade (i.e., PD, PC, or CC). These models test the assumption advanced by some scholars that control is the most pivotal construct in the functioning of intelligence (Engle et al., 1999). All of these models proved to be non-computable. Moreover, the fit of all models, where any of these three control factors is moved more than one position relative to their position in the original model, is very poor (all CFIs circa .7). Therefore, it is clear that speed of processing is the basic construct leading the cascade.

However, there is a class of models which fit the data equally well or better than the original model. In all of these models there is a hierarchy of three levels of processes that is structured as expected (i.e., speed → control (PD, PC, CC) → representational processes (WM, Infl, Reason). However, the order of the processes within each of the two higher levels may vary without seriously affecting the model fit. In fact, the best fitting model is one where the only difference from the original model is the interchange of positions between the PC and CC factors, χ^2 (146) = 169.397, p = .09, CFI = .975, RMSEA = .044 (90% confidence interval for RMSEA = .000–.071). This is the model shown in Fig. 6B. It can be seen that the only noticeable difference between this model and the original model shown in Fig. 6A is in the relation between each of these factors with working memory. Specifically, the PC–WM relation (−.77) is considerably higher than the CC–WM relation (−.55). Finally, in another model, the representational level was placed in between the speed of processing and the control level. That is, the cascade was specified as follows: [SP] → [WM → Infl → *R*] → [PD → PC → CC]. The fit of this model was worse than the fit of all other models that preserve the speed → control → representation order (χ^2 (146) = 197.931, p = .00, CFI = .944, RMSEA = .066 (90% confidence interval for RMSEA = .040–.088).

The simplex model above, despite its simplicity and elegance, does not allow the exact specification of the relations between each of the component process involved and the rest. This is due to the fact that, in this model, each factor involves, in addition to its factor-specific process, all of the processes residing lower in the hierarchy. In order to disentangle the relations among the various processes, a series of cascade models were tested where the factor-specific processes were isolated from the other processes included in a factor. In these set of models, in agreement with the findings of the simplex models above, speed of processing was taken as the most basic component that is part of all other processes. Therefore, this was the only independent factor in the model. Each of the other factors was regressed on speed of processing and the residuals of the factors residing lower than this factor in the hierarchy,

Table 1
Alternative simplex models and their fit indices (*df* = 146 in all models)

Regression models	χ^2	p	CFI
SP → PD → PC → CC → WM → Infl → *R*	178.71	0.03	0.965
R → Infl → WM → CC → PC → PD → SP	422.75	0.00	0.701
WM → Infl → *R* → SP → PD → PC → CC	423.12	0.00	0.701
WM → SP → PD → PC → CC → Infl → *R*	268.71	0.00	0.868
PD → SP → PC → CC → WM → Infl → *R*	Non-computable		
PC → SP → PD → CC → WM → Infl → *R*	Non-computable		
CC → SP → PD → PC → WM → Infl → *R*	Non-computable		
SP → CC → PC → PD → WM → Infl → *R*	416.17	0.00	0.708
SP → PC → CC → PD → WM → Infl → *R*	365.41	0.00	0.763
SP → CC → PD → PC → WM → Infl → *R*	399.93	0.00	0.726
SP → CC → PC → PD → WM → Infl → *R*	416.17	0.00	0.708
SP → PC → PD → CC → WM → Infl → *R*	176.09	0.04	0.968
SP → PD → CC → PC → WM → Infl → *R*	169.4	0.09	0.975
SP → PD → PC → CC → Infl → WM → *R*	177.74	0.04	0.966
SP → PD → PC → CC → WM → *R* → Infl	175.77	0.05	0.968
SP → PD → PC → CC → *R* → WM → Infl	176.69	0.04	0.967


A
SP₁
SP₂
.96
.95*
PD₁
PD₂
PD₃
.89*
.93
.87*
PC₁
PC₂
PC₃
SP
.66*
(68*)
.75
(.73)
.59*
.79
.91*
CC₁
CC₂
CC₃
PD
.45*
( )
.53
( )
.91*
.80
.85*
WM₁
WM₂
WM₃
.72*
( )
PC
.13
( )
.61
(.62)
.43*
.42
.60*
InfI₁
InfI₂
InfI₃
.72*
(.74*)
.31*
(.28*)
CC
-.07
(-.12)
.62
(.79)
.68*
.64
.42*
-.46*
(-.55*)
-.22
(.26)
-.59*
( )
WM
.41
(.59)
.65
(.66)
R₁
R₂
-.41*
(-.45*)
.02
(.00)
-.50*
( )
.00
(-.11)
InfI
.11
(.11)
.95
.86*
.47
(.45)
-.45*
(-.52*)
-.31*
(-.32*)
-.50*
( )
.17
(.09)
.42
(.64*)
R
B
SP
. 67*
. 74
PD
. 36*
. 54
. 76*
PC
. 61
. 32*
. 73*
CC
. 63
-. 61*
-. 48*
WM
. 91
-. 42*
InfI
. 57
. 40*
-. 46*
-. 56*
R

according to the Eqs. (1)–(6). Using the residuals of factors rather than the factors themselves ensures that each factor is purified from the components of speed and of all other factors residing lower than it. In this way the relation between processes can be specified without the confounding that may result from the fact that each factor involves other processes in addition to those specific to it (Gustafsson & Undheim, 1996). It may be noted here that of the various structural equation programs available only Bentler's (1995) EQS allows the researcher to enter the residuals of factors into structural equations as independent variables.

It is noted that all of the alternative models tested above vis-à-vis the simplex model were also tested vis-à-vis the original analytical cascade model, to be presented below, with similar results. That is, the original model formed according to Eqs. (1)–(6) was found to have perfect fit, χ^2 (130) = 110.889, $p = .886$, CFI = 1.000, RMSEA = .000 (90% confidence interval for RMSEA = .000–.027). The fit of all models where the speed → control → representational processes hierarchy was preserved but adjacent factors were interposed within each of the two higher levels of the hierarchy was identical to the fit of the original model. All other models were found to have poor fit (all CFIs circa .7). Thus, below we will present the original model and some variations of it aimed to clarify the relative power of various factors within the hierarchy.

The original analytical model is illustrated in Fig. 7A. It is clear that speed of processing is a very powerful component of all other processes represented in this cascade. Perceptual control is an equally powerful component of all of the processes residing higher than it. Perceptual discrimination and working memory do have moderate relations with processes residing higher. Conceptual control and information integration are highly predicted by more fundamental processes but do not provide any additional predictive power with respect to more complex processes. The three representational processes studied here are moderately but not significantly related to each other, obviously because their relations are mediated by the more fundamental processes, mainly speed and perceptual control.

It is noted here that the lack of relations between conceptual control and any of higher level processes was not expected. To test if this is because the conceptual control factor is redundant to the perceptual control factor, the model above was retested after dropping the perceptual control factor. The fit of this model was also perfect, χ^2 (88) = 76.675, $p = .800$, CFI = 1.000, RMSEA = .000 (90% confidence interval for RMSEA = .000–.039). It can be seen in Fig. 7A that this manipulation did not affect the relations between the conceptual control factor and any of the other factors. It is clear, therefore, that the aspect of executive control represented by the conceptual control factor is not related to any of the processes represented by the three higher level factors. However, this manipulation did result in considerable strengthening of the relations between working memory and both information integration (it increased from .41 to .59, which is equivalent to a change in effect size from .18 to .26) and reasoning (it increased from .42 to .64, which is equivalent to a change in effect size from .20 to .28). We take this finding to indicate that the relations between working memory and information integration or reasoning are mediated by the control processes implicated in perceptual control activated by Stroop-like tasks.

One might argue that the excellent fit of the model above is due to the fact that it is saturated. Obviously, a more parsimonious model with an acceptable fit would be preferable over a saturated model. This model is shown in Fig. 7B.

It can be seen that all non-significant relations, but the working memory-reasoning relation that was significant in the second model, were dropped in this model. The fit was excellent, χ^2 (140) = 144.948, $p = .370$, CFI = .995, RMSEA = .021 (90% confidence interval for RMSEA = .000–.057). This model makes it clear that speed of processing is the central factor closely related to all other factors, that perceptual control is an equally powerful factor for working memory and reasoning, and that reasoning is also related to working memory.

3.2. Development

3.2.1. Processing efficiency

To specify the pattern of development of the various processes studied here a series of ANOVAs with repeated measures on the last factor were run. The first involved the four means standing for each of the four speeded performance factors, that is, speed of processing, perceptual discrimination, perceptual control, and conceptual control. This is a 6 (the six age groups) × 2 (the two genders) × 4 (the four processing efficiency means) ANOVA with repeated measures on the last factor. The main effect of age was highly significant and strong, $F(5, 101) = 20.070$, $p < .0001$, $\eta^2 = .50$, reflecting the fact that response times decreased systematically and extensively with age. The main effect of gender $F(1, 101) = .442$, $p > .05$, $\eta^2 = .00$, and the age × gender interaction, $F(5, 101) = 1.142$, $p > .05$, $\eta^2 = .07$, were non-significant. The main effect of processing efficiency was

Fig. 7. A. The model of the structural relations between processes. Note 1: Model fit for raw correlations: χ^2 (130) = 110.889, $p = .886$, CFI = 1.000, RMSEA = .000 (90% confidence interval for RMSEA = .000 – .027). Note 2: Parameter estimates in parentheses refer to the model after dropping the PC factor. Note 3: Asterisks denote significance at the .05 level. Note 4: All coefficients are taken from the standardized solutions. Note 5: SP: speed; PD: perceptual discrimination; PC: perceptual control; CC: conceptual control; WM: working memory; InfI: information integration; *R*: reasoning. B. The model of structural relations between processes after dropping non-significant relations. Note 1: Observed variables are omitted, because they do not differ from those shown in the complete model presented in Fig. 7A. Note 2: Asterisks, coefficients, and factor names are specified in Fig. 7A notes.

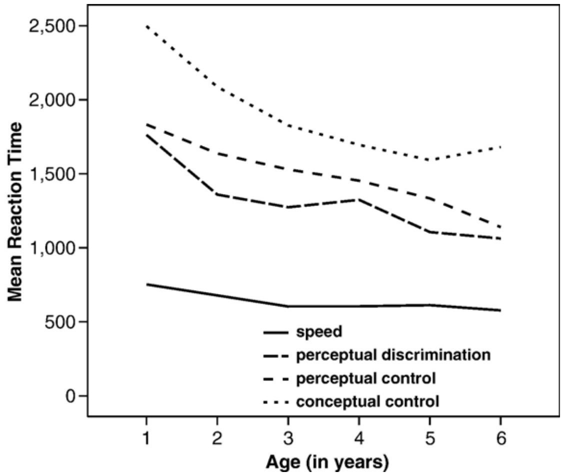


Fig. 8. Processing efficiency as a function of age and process.

extremely strong, Wilk's lambda = .04, $F(3, 99) = 742.184$, $p < .0001$, $\eta^2 = .96$, reflecting the fact that from low to high the four mean reaction times were ordered as follows: Speed, PD, PC, CC (differences between Speed and PD, $F(1,102) = 1073.325$, PD and PC, $F(1,102) = 49.240$, and PC and CC, $F(1,102) = 99.140$, were highly significant, all p values were less than .001). Obviously, this order fully conforms to what would have to be expected according to the additive factor composition of the four processes. The interaction between age and processing efficiency was significant and strong, Wilk's lambda = .44, $F(15, 273) = 4.377$, $p < .0001$, $\eta^2 = .24$, reflecting the fact, illustrated in Fig. 8, that the four measures of processing efficiency were differentially associated with age.

For instance, change in speed of processing is smoother and less steep than in perceptual discrimination and control, indicating that mastering these processes, although built on the general qualities reflected in speed, takes longer and it comes in phases. We will further embark on this issue in the analysis to be presented below.

3.2.2. Working memory

To chart the development of working memory, the two means representing performance on the visuo-spatial and quantitative working memory tasks, were subjected to a 6 (the six age groups) × 2 (the two genders) × 2 (the two means) ANOVA with repeated measures on the last factor. The effect of age was highly significant and strong, $F(5, 84) = 13.160$, $p < .0001$, $\eta^2 = .44$, ($F(5, 70) = 4.204$, $p < .002$, $\eta^2 = .23$)[1] suggesting that performance improved systematically throughout the age span studied here, in some periods faster than in others, such as the period from 6 to 7, 8 to 9, and 10 to 11 years of age (see Fig. 9). The effect of gender was significant, $F(1, 84) = 5.741$, $p < .02$, $\eta^2 = .06$, ($F(1, 70) = 7.214$, $p < .009$, $\eta^2 = .09$) reflecting the fact that boys performed better than girls. The task effect was highly significant and strong, Wilk's lambda = .49, $F(1, 84) = 86.154$, $p < .0001$, $\eta^2 = .51$ (Wilk's lambda = .99, $F(1, 70) = .729$, $p > .05$, $\eta^2 = .01$), indicating that performance on the visuo-spatial tasks was clearly better than performance on the numerical tasks.

However, the significant interaction between age and memory type, Wilk's lambda = .87, $F(5, 84) = 2.529$, $p < .04$, $\eta^2 = .13$, (Wilk's lambda = .91, $F(5, 70) = 1.413$, $p > .05$, $\eta^2 = .09$) reflected the fact that the difference between spatial and numerical tasks tended to decrease with age. Finally, the interaction between memory type and gender was significant, Wilk's lambda = .92, $F(1, 84) = 6.987$, $p < .01$, $\eta^2 = .08$, (Wilk's lambda = .92, $F(1, 70) = 6.022$, $p < .02$, $\eta^2 = .08$), suggesting that performance on the visuo-spatial tasks was the same in the two genders but boys outperformed girls on both of the numerical tasks.

According to the structural model presented above, a significant part of the variance of performance on the working memory tasks was associated with the various measures of processing efficiency and that these measures were closely related with age. Therefore, it was interesting to test how the differences discussed above were affected when the effects of processing efficiency were statistically partialled out. In the sake of this aim, the analyses presented above were re-run with the four means standing for the four processing efficiency factors used as covariates. The results of this analysis are shown in parentheses next to the results of the analysis which did not involve any covariates. It can be seen that the effects of age, although extensively diminished (the variance accounted for by age dropped from 44% to 23%), remained significant

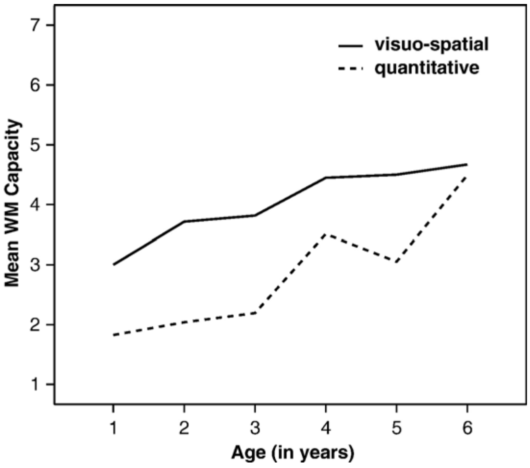


Fig. 9. Visuo-spatial and quantitative memory as a function of age.

---

[1] Statistics in parenthesis were obtained from the same analysis after introducing the covariates to be specified below.

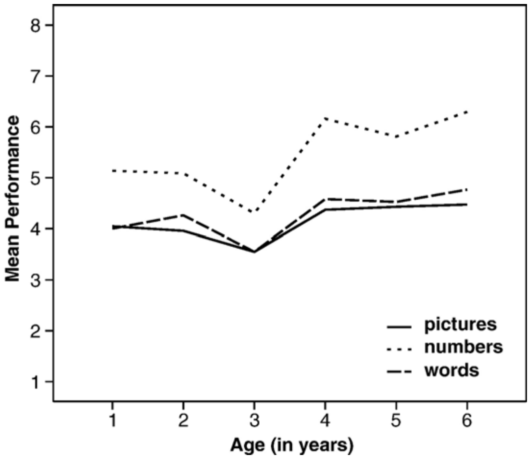


Fig. 10. Performance on the information integration task as a function of age and symbolic medium.

and strong. Therefore, the development of working memory, although partially dependent on these other processes, is driven by factors that are particular to it. However, the differences between the two types of working memory disappeared completely, suggesting that they emanated from their differential dependence on the processes represented by these covariates.

3.2.3. Integration of information

The third analysis involved performance on the components of integration of information task, that is, the verbal, the numerical, and the figural component. This was a 6 (the six age groups) × 2 (the two genders) × 3 (the three measures mentioned above) ANOVA, with repeated measures on the last factor. The main effect of age was significant and strong, $F(5, 110)=6.208$, $p<.0001$, $\eta^2=.22$, ($F(5, 67)=3.239$, $p<.01$, $\eta^2=.20$). Inspection of Fig. 10 suggests that performance on this task was related to age in a U-shaped fashion across all three symbolic media. That is, it dropped from first through third grade and then rose extensively from third to fourth grade, when it basically remained stable until sixth grade. In general, U-shaped growth is considered to indicate that the process of interest undergoes a qualitative shift from a simpler to a more complex strategy. Performance drops at the initial phase of the shift when the thinker starts to use the new process without having full mastery of it. In the present case, the shift might be related to the information scanning and integration strategies adopted. That is, it might be the case that at the beginning children are careful to scan information in the field because they are rather slow and inexperienced. As they become faster in processing speed they become confident enough to make decisions quickly but their experience is not enough to allow them to cope with the task. When they start to realize their inefficiency they become more exhaustive in their search and integration strategies. This shift will eventually lead to improved performance.

To control for the effects of processing efficiency and working memory on the patterns of differences described above, the analysis above was re-run using the four processing efficiency and the mean of performance on the two types of working memory as covariates. The results of these analyses, shown in parentheses next to the results of the analyses which did not involve any covariates, indicate that the effect of age remained significant and strong (η^2 dropped from .22 to .20), suggesting that age differences in information integration are germane to these processes rather than to processing efficiency and working memory. Interestingly, however, the effect of symbolic medium did become low and non-significant, suggesting that the differences between the three variants of the task were due to their differential dependence on processing efficiency and working memory.

3.2.4. Reasoning

To specify the development of reasoning, the means of performance on inductive and deductive reasoning were used in a 6 (the six age groups) × 2 (the two genders) × 2 (inductive vs. deductive reasoning) ANOVA, with repeated measures on the last factor. The effect of age was highly significant and strong, $F(5, 128)=26.353$, $p<.0001$, $\eta^2=.51$, ($F(5, 66)=10.775$, $p>.0001$, $\eta^2=.45$), reflecting the fact (see Fig. 11) that performance increased systematically from 6 through 10 years of age.

There was no difference between genders in reasoning, $F(1, 128)=.600$, $p>.05$, $\eta^2=.02$, lending support to Lynn's (1999) theory that gender differences in intelligence do not appear before the end of puberty. The difference between the two types of reasoning was also significant and moderate in size, Wilk's lambda = .83, $F(1, 128)=26.612$, $p<.0001$, $\eta^2=.17$ (Wilk's lambda = .99, $F(1,66)=.034$, $p>.05$, $\eta^2=.00$), reflecting the fact that performance on inductive reasoning was higher than performance on deductive reasoning. No interaction between reasoning and any other factor was significant, suggesting that performance on inductive reasoning was consistently higher than performance on deductive

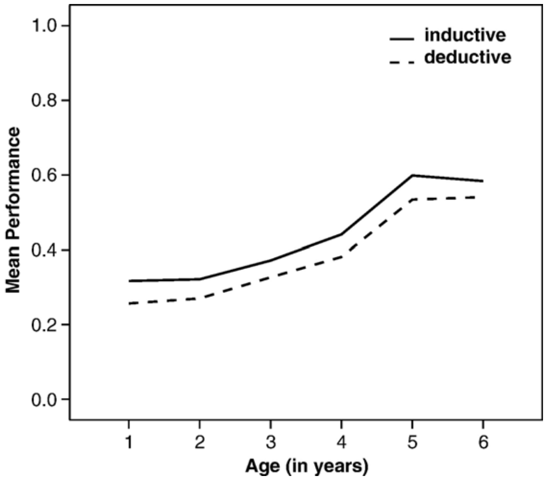


Fig. 11. Inductive and deductive reasoning as a function of age.

reasoning. Controlling for the effect of processing efficiency, working memory, and integration of information did not basically affect the effect of age but it did cause the differences between the two types of reasoning and the age × reasoning interaction to vanish. It needs to be noted, however, that of the various factors included in the analysis as covariates, the strongest impact came from perceptual, $F(1, 66)=12.004$, $p<.001$, $\eta^2=.15$, and conceptual control, $F(1, 66)=4.817$, $p<.03$, $\eta^2=.07$.

Three conclusions are suggested by this pattern of effects. First, the development of reasoning involves a large reasoning-specific component that goes beyond sheer processing efficiency, working memory, and information integration. Second, any age differences in reasoning result from executive processes associated with the control of interference. Third, differences between inductive and deductive reasoning result from the differential dependence of these two types of reasoning on processing efficiency, working memory, and information integration. That is, deductive reasoning, as a more constrained and therefore more effortful kind of reasoning, seems to require more support from the various processes ensuring mental efficiency. If not available, deduction will suffer.

4. Discussion

The findings of this study were generally in line with our predictions about the structure and development of the cognitive processes examined here. In the discussion below we will try to integrate these findings into a common framework and discuss their implications for future research.

4.1. Structure

The structural models capturing the relations between the various processes suggest that *g* cannot be identified with a single construct or dimension. It is multiply determined by several processes which seem to be embedded in each other and to interact dynamically. Although hierarchically structured from the simplest (i.e., speed of processing) to the most complex (i.e., reasoning), these processes may functionally be differentiated into three overall levels of processing: speed of processing, control of processing, defined by processes such as perceptual discrimination, perceptual and conceptual control, and a higher representational level defined by storage, integration of information, and inference. However, it is stressed that hierarchical organization within the two higher levels is quite flexible. That is, although it tends to be as assumed, other hierarchies might also hold. This finding is highly interesting in that it suggests that any of the various control processes or any of the various representational processes may be called upon or run in parallel, according to the requirements of the task at hand, without requiring the activation of the other processes within their level. In fact, one might argue that one of the main aims of cognitive development is to coordinate these processes or enable the thinker to choose between them according to the task at hand. Interestingly, van der Maas et al. (2006), have recently shown that the positive manifold underlying *g* can be accounted for by the dynamic reciprocal relations between cognitive processes rather than by an underlying common cognitive or biological process or capacity. The findings of the present study lend support to this dynamical conception of *g* and reveal how the various processes are interrelated.

Specifically, speed is so powerful that it defines a level on its own. It is reminded that a large part of the variance of the factors at the other two levels was accounted for by speed. The other three dimensions of processing efficiency that define the level of control, that is, perceptual discrimination and perceptual and conceptual control, represent more specialized aspects of efficiency that operate on the common quality represented by speed. Specifically, perceptual discrimination is part of both types of control suggesting that the comparison processes are part of any aspect of executive control. However, perceptual control is independent of conceptual control, indicating that each of them specializes on the management of different types of information. It is notable that recent neuroimaging research is consistent with this finding. Specifically, several studies show that different types of conflict in the Stroop paradigm are served by different networks in the brain. All of these networks are located in the anterior cingulate, the prefrontal, and the parietal cortex and they are adjacent to each other (Egner & Hirsch, 2005; van Veen & Carter, 2005).

The relations between working memory, information integration, and reasoning, with each of the dimensions of processing efficiency and with each other were clear. Specifically, each of these processes was about equally associated with the same two dimensions of efficiency, namely speed and perceptual control (about 20–25% of their variance was accounted for by each of these two dimensions of efficiency). The relations between the three representational processes themselves were moderate. Surprising as it might seem, this finding indicates that the relations between these representational processes are mediated by these two powerful aspects of processing efficiency. This conclusion is strongly supported by the model where the perceptual control factor was dropped. It is reminded that in this case the relations between working memory with both information integration (35% of variance) and reasoning (41% of variance) increased remarkably, suggesting that it is the executive component of working memory that functions as the main binding factor between working memory and integration of information and reasoning. Unsworth and Engle (2005) have recently also found that attention mediates the relation between working memory and fluid intelligence.

It is also reminded that conceptual control was not related to any of the three representational processes studied here, suggesting that this aspect of control is not part of information storage, integration, or reasoning. Interesting as it might be, this finding was not expected. It indicates, however, that the management of conflict between perceptual information and conceptual knowledge is less important for these processes than the management of conflict between perceptual dimensions. It might be the case that the latter type of control requires attention focusing that is part of all three representational dimensions, whereas the former type of control requires coordination between perceptual information and information in long-term memory that is irrelevant for any of these three dimensions.

4.2. Development

All processes investigated here were found to be systematically associated with age. Older children responded faster to all speeded performance tasks, recalled more items in all working memory tasks, handled the information integration tasks better, and solved increasingly more complex and abstract reasoning problems, despite having less assistance in solving the reasoning tasks. This general pattern suggests that there is a general developmental cascade where growth effects propagate bottom-up from speed to inference. That is, increases in speed facilitate improvements in control and these, in turn, facilitate improvements in representational processes, such as working memory capacity, information integration strategies, and inferential processes. Speed and perceptual control were found to be the main driving forces of this developmental cascade. It needs to be noted here that the pattern of age differences in information integration suggests that improvements in speed and control of processing are not always linearly related to improvements in information management and inferential processes. That is, these improvements may initially cause a disorganization of available information integration and inferential patterns with an ensuing temporary drop in performance until the construction of new strategies that are consistent with the new level of processing efficiency.

Moreover, each of the factors in the cascade only partially contributes to the development of the factors residing higher, especially when we come to the relations between efficiency factors and representational processes. Therefore, the actualization of these possibilities in the various representational realms requires that the skills, strategies, and mental operations (and the necessary neural networks) for storing and integrating information and drawing inferences are constructed as such. This interpretation is suggested by the finding that partialling out the effect of processing efficiency only slightly affects the effects of age concerning all other functions. That is, there are changes in storing, integrating information, and reasoning that are germane to each of these systems of processes. Therefore, the common developmental possibilities emerging from the qualities represented by processing speed, and, common integrative possibilities represented by executive control, coexist with process-specific and domain-specific constructions.

In conclusion, this study uncovered the many processes involved in general intelligence at various levels of organization and specified how these processes are interrelated and develop during childhood. Several important issues are still open and must be dealt with by future research. Specifically, the structural and developmental patterns identified here must be verified in other populations and other periods of life, such as adolescence. Also, longitudinal research is needed to verify the cascade structure of relations over developmental time. Finally, neuroscience research is needed to explore the structural and functional equivalents of the processes and relations identified here in the brain and in brain development (see Jung & Haier, in press; Demetriou and Mouyi, in press; Demetriou et al., in press). Obviously, the grand neuro-cognitive developmental theory of intelligence to come would have to integrate brain with functional and subjective maps of mental functions into a common landscape.

Acknowledgements

Authors are listed alphabetically because they contributed equally to the design and execution of the study.

Thanks are due to Jan Boom, Roberto Colom, Jan-Eric Gustafsson, Leonidas Kyriakides, Wendy Johnson, and an anonymous reviewer for their constructive comments on an earlier version of this article.

Appendix A

Table A1
Means and standard deviations (in parentheses) of the variables used in SEM and ANOVA as a function of age

Age	Task																			
	SP_1	SP_2	PD_1	PD_2	PD_3	PC_1	PC_2	PC_3	CC_1	CC_2	CC_3	WM_1	WM_2	WM_3	WM_4	$InfI_1$	$InfI_2$	$InfI_3$	R_1	R_2
6	745.47	759.62	1682.78	1785.38	1764.10	1618.22	1864.36	2099.65	2799.35	2601.15	2155.05	2.86	4.14	1.93	1.49	5.14	4.00	4.05	0.32	0.26
	(83.65)	(77.88)	(329.88)	(391.79)	(279.07)	(453.99)	(457.32)	(270.76)	(702.23)	(525.25)	(511.80)	(1.75)	(1.37)	(2.18)	(1.43)	(1.46)	(1.23)	(1.13)	(0.10)	(0.09)
7	674.05	683.00	1345.81	1377.65	1333.20	1427.79	1678.58	1803.13	2208.13	2275.40	1775.81	3.53	4.43	2.51	1.40	5.09	4.26	3.96	0.32	0.27
	(83.01)	(80.29)	(298.97)	(336.09)	(298.72)	(505.74)	(353.41)	(380.28)	(674.79)	(509.37)	(402.76)	(1.26)	(1.06)	(2.27)	(1.49)	(1.31)	(1.36)	(1.30)	(0.13)	(0.13)
8	605.55	601.04	1287.37	1285.59	1247.94	1579.86	1471.33	1535.23	1895.57	1959.81	1624.59	3.50	4.32	2.25	2.00	4.30	3.55	3.55	0.37	0.33
	(88.93)	(117.68)	(315.88)	(290.96)	(264.60)	(729.57)	(320.63)	(270.71)	(459.63)	(556.96)	(445.12)	(2.24)	(1.55)	(2.27)	(2.04)	(1.59)	(1.10)	(1.15)	(0.09)	(0.10)
9	593.73	615.20	1302.16	1358.49	1311.27	1491.38	1419.68	1433.25	1867.88	1691.07	1526.70	4.57	4.97	2.77	3.53	6.16	4.58	4.37	0.44	0.38
	(107.77)	(106.95)	(306.70)	(338.04)	(309.65)	(417.30)	(428.81)	(291.51)	(446.36)	(352.82)	(325.62)	(0.93)	(0.15)	(2.04)	(1.92)	(1.17)	(1.43)	(1.61)	(0.12)	(0.17)
10	617.18	608.15	1135.44	1061.26	1122.25	1272.55	1375.22	1349.77	1789.43	1553.15	1435.05	4.48	4.93	2.33	3.45	5.81	4.52	4.43	0.60	0.53
	(94.94)	(79.93)	(262.70)	(253.42)	(256.90)	(284.04)	(273.10)	(290.41)	(368.98)	(389.76)	(377.55)	(0.93)	(0.24)	(1.94)	(2.00)	(1.21)	(1.03)	(1.03)	(0.15)	(0.13)
11	573.71	581.24	1041.43	1039.35	1107.72	1195.17	1076.18	1149.12	1854.34	1802.24	1384.25	4.95	4.93	4.13	4.41	6.29	4.76	4.47	0.58	0.54
	(83.78)	(87.76)	(178.80)	(169.49)	(235.61)	(508.75)	(185.29)	(197.32)	(543.12)	(498.25)	(302.689	(0.86)	(0.24)	(2.04)	(1.71)	(1.65)	(0.97)	(1.18)	80.19)	(0.16)

(Speed 1 (left)=SP_1, 2. Speed 2 (right)=SP_2, 3. Perceptual discrimination 1 (conceptual relation)=PD_1, 4. Perceptual discrimination 2 (functional relation)=PD_2, 5. Perceptual discrimination 3 (physical relation)=PD_3, 6. Perceptual control 1 (word)=PC_1, 7. Perceptual control 2 (figure)=PC_2, 8. Perceptual control 3=PC_3, 9. Conceptual control 1 (conceptual relation)=$CC1_2$, 10. Conceptual control 2 (functional relation)=CC_2, 11. Conceptual control 3 (physical relation)=CC_3, 12. Visuo-spatial working memory=WM_1, 13. Visuo-spatial working memory (configurations) WM_3, 14. Numerical working memory (number symbols)=WM_3, 15. Numerical working memory (dot variant)=WM_4, 16. Information integration (word)=$InfI_1$, 17. Information integration (object)=$InfI_2$, 18. Information integration (number)=$InfI_3$, 19. Induction=R_1, 20. Deduction=R_2).

Table A2

Correlations, means, and standard deviations for all variables used in structural equation models

	Age	SP_1	SP_2	PD_1	PD_2	PD_3	PC_1	PC_2	PC_3	CC_1	CC_2	CC_3	WM_1	WM_2	WM_3	InfI_1	InfI_2	InfI_3	R_1	R_2
SP_1	−.498**																			
SP_2	−.502**	.925**																		
PD_1	−.564**	.599**	.634**																	
PD_2	−.604**	.594**	.624**	.852**																
PD_3	−.563**	.572**	.609**	.806**	.823**															
PC_1	−.287**	.300**	.301**	.336**	.376**	.321**														
PC_2	−.578**	.514**	.520**	.573**	.635**	.578**	.434**													
PC_3	−.711**	.551**	.544**	.581**	.626**	.623**	.431**	.680**												
CC_1	−.469**	.588**	.571**	.544**	.491**	.551**	.297**	.427**	.507**											
CC_2	−.529	.562	.574	.530	.474	.442	.151	.369	.450	.71										
CC_3	−.521**	.562**	.542**	.537**	.489**	.540**	.219*	.414**	.508**	.71**	.692**									
WM_1	.303**	−.281**	−.361**	−.226*	−.26**	−.218*	−.144	−.189*	−.31**	−.228*	−.24**	−.257**								
WM_2	.292**	−.148	−.131	−.159	−.164	−.225*	−.172	−.340**	−.30**	−.116	−.093	−.096	.242**							
WM_3	.537**	−.360**	−.330**	−.38**	−.327**	−.302**	−.225*	−.366**	−.38**	−.243*	−.33**	−.298**	.15	.328**						
InfI_1	.221*	−.145	−.115	−.096	−.100	−.120	−.137	−.152	−.179	−.087	−.120	−.121	.251**	.252*	.188					
InfI_2	.118	.018	−.039	−.060	−.080	−.043	−.076	−.139	−.142	.030	−.019	−.051	.252**	.129	.150	.364**				
InfI_3	.288**	−.135	−.157	−.086	−.055	−.135	−.315**	−.189*	−.24**	−.176	−.166	−.104	.182*	.251*	.333**	.470**	.258**			
R_1	.649**	−.286**	−.336**	−.37**	−.41**	−.36**	−.368**	−.489**	−.51**	−.29**	−.32**	−.259**	.350**	.383**	.511**	.348**	.203*	.41**		
R_2	.638**	−.262**	−.307**	−.41**	−.45**	−.43**	−.302**	−.467**	−.53**	−.22*	−.28**	−.204*	.285**	.255**	.408**	.234**	.191*	.40**	.77**	
Mean	9.29	635.02	640.9	1300.8	1318.8	1315.8	1431.6	1435.8	1586.6	2064.7	1978.5	1643.6	4.63	2.67	2.75	4.26	4.14	5.43	.442	.389
SD	1.76	106.97	110.12	349.21	391.78	350.68	516.96	485.34	574.99	636.18	589.94	459.41	.984	2.19	2.09	1.24	1.27	1.54	.178	.176

Note: significance at .05 (*) and .01 (**) level (2-tailed).

(Speed 1 (left)=SP_1, 2. Speed 2 (right)=SP_2, 3. Perceptual discrimination 1 (conceptual relation)=PD_1, 4. Perceptual discrimination 2 (functional relation)=PD_2, 5. Perceptual discrimination 3 (physical relation)=PD_3, 6. Perceptual control 1 (word)=PC_1, 7. Perceptual control 2 (figure)=PC_2, 8. Perceptual control 3=PC_3, 9. Conceptual control 1 (conceptual relation)=$\mathrm{CC1}_2$, 10. Conceptual control 2 (functional relation)=CC_2, 11. Conceptual control 3 (physical relation)=CC_3, 12. Visuo-spatial working memory=WM_1, 13. Numerical working memory (number symbols)=WM_2, 14. Numerical working memory (dot variant)=WM_3, 15. Information integration (word)=InfI_1, 16. Information integration (object)=InfI_2, 17. Information integration (number)=InfI_3, 18. Induction=R_1, 19. Deduction=R_2).

References

Bentler, P. M. (1995). *EQS structural equations program manual.* Encino, CA: Multivariate Software Inc.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies.* New York: Cambridge University Press.

Case, R. (1985). *Intellectual development: Birth to adulthood.* New York: Academic Press.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Minkoff, S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence*, *30*, 163−183.

Demetriou, A. (2002). Tracing psychology's invisible g_{iant} and its visible guards. In R. J. Sternberg & E. L. Grigorenko (Eds.), *The general factor of intelligence: How general is it?* (pp. 3−18). Mahwah, NJ: Lawrence Erlbaum Associates.

Demetriou, A. (2006). Dissecting *g*. *Behavioral and Brain Sciences*, *206*, 22−24.

Demetriou, A., Christou, C., Spanoudis, G., & Platsidou, M. (2002). *The development of mental processing: Efficiency, working memory, and thinking.* Monographs of the Society of Research in Child Development, 67, Serial Number 268.

Demetriou, A., & Mouyi, A. (in press). A roadmap for integrating brain with mind maps. *Behavioral and Brain Sciences*.

Demetriou, A., Spanoudis, G., & Mouyi, A. (in press). A Three-level Model of the Developing Mind: Functional and Neuronal Substantiation. In M. Ferrari & L. Vuletic (Eds.), *The Developmental Relations between Mind, Brain, and Education: Essays in honor of Robbie Case*. New York: Springer.

Demetriou, A., Zhang, X. K., Spanoudis, G., Christou, C., Kyriakides, L., & Platsidou, M. (2005). The architecture and development of mental processing: Greek, Chinese or Universal? *Intelligence*, *33*, 109−141.

Dempster, F. N. (1991). Inhibitory processes: A neglected dimension of intelligence. *Intelligence*, *15*, 157−173.

Detterman, D. K. (2002). General intelligence: Cognitive and biological explanations. In R. J. Sternberg & E. L. Grigorenko (Eds.), *The general factor of intelligence: How general is it?* (pp. 223−243). Mahwah, NJ: Lawrence Erlbaum Associates.

Egner, T., & Hirsch, J. (2005). The neural correlates and functional integration of cognitive control in a Stroop task. *NeuroImage*, *24*, 539−547.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General*, *128*, 309−331.

Embrertson, S. E. (1995). The role of working capacity and general processes in intelligence. *Intelligence*, *20*, 169−189.

Garlick, D. (2002). Understanding the nature of the general factor of intelligence: the role of individual differences in neural plasticity as an explanatory mechanism. *Psychological Review*, *109*, 116−136.

Gustafsson, J.-E., & Carlstedt, B. (2006). Abilities and grades as predictors of achievement: The Encapsulation theory. Paper presented at the annual meeting of the American Psychological Association, New Orleans, August 10–13.

Gustafsson, J. E., & Undheim, J. O. (1996). Individual differences in cognitive functions. In D. C. Berliner & R. C. Calfee (Eds.), *Handbook of educational psychology* (pp. 186−242). New York: Macmillan.

Humphreys, L. G., & Stark, S. (2002). General intelligence: Measurement, correlates, and interpretations of the cultural-genetic construct. In R. J. Sternberg & E. L. Grigorenko (Eds.), *The general factor of intelligence: How general is it?* (pp. 87−115). Mahwah, NJ: Lawrence Erlbaum Associates.

Hunt, E. (1980). Intelligence as an information processing concept. *British Journal of Psychology*, *71*, 449−474.

Jensen, A. R. (1998). *The G factor: The science of mental ability.* New York: Praeger.

Jensen, A. R. (2002). Psychometric *g*: Definition and substantiation. In R. J. Sternberg & E. L. Grigorenko (Eds.), *The general factor of intelligence: How general is it?* (pp. 39−53). Mahwah, NJ: Lawrence Erlbaum Associates.

Jung, R. E., & Haier, R. J. (in press). The parieto-frontal integration theory (P-FIT) of intelligence: Converging neuroimaging evidence. *Behavioral and Brain Sciences*.

Kail, R. (1991). Developmental functions for speed of processing during childhood and adolescence. *Psychological Bulletin*, *109*, 490−501.

Kail, R., & Salthouse, T. A. (1994). Processing speed as a mental capacity. *Acta Psychologica*, *86*, 199−225.

Kovas, Y., & Plomin, R. (2006). Generalist genes: Implications for the cognitive sciences. *Trends in Cognitive Sciences*, *10*, 198−203.

Kyllonen, P., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity? *Intelligence*, *14*, 389−433.

Lynn, R. (1999). Sex differences in intelligence and brain size: A developmental theory. *Intelligence*, *27*, 1−12.

Miller, L. T., & Vernon, P. A. (1996). Intelligence, reaction time, and working memory in 4 to 6 year-old children. *Intelligence*, *22*, 155−190.

Naglieri, J. A., & Das, J. P. (2002). Practical implications of general intelligence and PASS cognitive processes. In R. J. Sternberg & E. L. Grigorenko (Eds.), *The general factor of intelligence: How general is it?* (pp. 55−84). Mahwah, NJ: Lawrence Erlbaum Associates.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology*, *9*, 353−383.

Paivio, A. (1975). Perceptual comparisons through the mind's eye. *Memory and Cognition*, *3*, 635−647.

Posner, M. I., Rothbart, M. K., & Sheese, B. E. (2007). Attention genes. *Developmental Science*, *10*, 24−29.

Posthuma, D., & de Geus, E. J. C. (2006). Progress in the molecular-genetic study of intelligence. *Current Directions in Psychological Science*, *15*, 151−155.

Spearman, C. E. (1927). *The abilities of man.* London: MacMillan.

Stankov, L., & Roberts, R. (1997). Mental speed is not the 'basic' process of intelligence. *Personality and Individual Differences*, *22*, 69−84.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders method. *Acta Psychologica*, *30*, 276−315.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643−662.

Unsworth, N., & Engle, R. W. (2005). Working memory capacity and fluid abilities: Examining the correlation between operation span and Raven. *Intelligence*, *33*, 67−81.

van der Maas, H. L. J., Dolan, C. V., Grasman, R. P. P. P., Wicherts, G. J. M., Huizenga, H. M., & Raijmakers, M. E. J. (2006). A dynamical model of general intelligence: The positive manifold of intelligence by mutualism. *Psychological Review*, *113*, 842−861.

van Veen, V., & Carter, C. S. (2005). Separating semantic conflict and response conflict in the Stroop task: A functional MRI study. *NeuroImage*, *27*, 497−504.

Zelazo, P. D., & Frye, D. (1998). Cognitive complexity and control: II. The development of executive function in childhood. *Current Directions in Psychological Science*, *7*, 121−126.