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Decomposing the influence of mental processes on academic performance

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ABSTRACT

We explored relations between academic performance and cognition from 9 to 15 years of age. Participants were examined on executive control processes, reasoning in several domains, self-evaluation of performance in these domains, and language. Structural equation modelling showed that cognitive and language ability highly predicted school performance. These relations changed with age; cognitive flexibility, working memory and reasoning dominated from 9 to 11 and reasoning and language dominated from 13 to 15 years. Self-evaluation was related with academic performance only in secondary school, but this relation was masked by reasoning. SES influenced school achievement directly on top of cognitive influences in both primary and secondary school. The implications for cognitive developmental theory and educational implications are discussed.

1. Introduction

This study examined how performance at school relates to various dimensions of cognition. We decomposed this relation into specific processes involved in cognition, such as executive control, reasoning, language and cognitive self-evaluation, and specified if they relate to school performance differently at different levels of school education. Below we first summarize current research about the organization and development of these mental processes. We then summarize research showing how these processes relate to academic achievement. Finally, we state predictions to be tested by our study.

1.1. Intelligence

1.1.1. Organization

The hierarchical interpretation of mental processes dominates in psychometric (Carroll, 1993) and brain models (Haier, 2017) of the human mind. According to this interpretation, mental abilities are organized in three major hierarchical levels. At the task level, there are specific processes related to specific tasks, such as addition in mathematics, visualization in space, classifying objects, etc. At this level, specificities of task content and the context involving the task may be important. At a higher level, task-specific skills are organized in several broad domains, identified by mental processes shared by tasks. For instance, numerical operations and the mental number line in mathematics, mental rotation and mental imagery in spatial reasoning, sorting and class reasoning in classification, etc. Although the exact number, identity, and degree of functional autonomy of the domains are still disputed, some domains are recognized across disciplines of psychological research. For instance, spatial, categorical, quantitative, causal, social, and verbal reasoning emerged as distinct domains in differential, cognitive, developmental, and educational psychology (Carroll, 1993; Case, 1992; Case, Demetriou, Platsidou, Kazi, 2001; Demetriou & Spanoudis, 2018; Gardner, 1983; Thurstone, 1973).

At still a higher level, all domains relate to a higher-order factor, general intelligence or g, reflecting the fact that all mental processes correlate with each other. Although widely accepted, the nature of g is still under strong dispute. Through the years, it has been associated with three types of domain-independent processes. First is reasoning in its various manifestations, including inductive, analogical, and deductive reasoning (Carroll, 1993; Jensen, 1998; Spearman, 1927). In current psychometric theory, this factor is basically identical with fluid intelligence (gf) (Gustafsson & Undheim, 1996). Later, several processes which reflect efficiency in representing and processing information were found to independently relate with psychometric g. These include processing speed (Coyle, 2017; Kail, Lervag, & Hulme, 2015), inhibition and attention control (Arsalidou & Pascaul-Leone, 2016; Blair, 2006; Zelazo, 2015), and working memory (Baddeley, 2012; Case, 1992;

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Halford, Wilson, & Phillips, 1998; Kyllonen & Christal, 1990; Pascual-Leone, 1970). Finally, recent research suggested that various aspects of metacognition (Demetriou et al., 2018; Efklides, 2008) relate with g. These include awareness of mental processes and their mental load (Demetriou & Kazi, 2006; Kazi, Demetriou, Spanoudis, Zhang, & Wang, 2012), awareness of the origins of knowledge (Spanoudis, Demetriou, Kazi, Giorgala, & Zenonos, 2015), and self-evaluation of one's own performance on cognitive tasks (Demetriou & Efklides, 1989; Makris, Tahmatzidis, Demetriou, & Spanoudis, 2017).

Makris et al. (2017) showed recently that psychometric g is a complex additive function of all of these processes: attention control, shifting flexibility, working memory, reasoning, and awareness accounted for 27%, 18%, 27%, 19%, and 7% the variance of g, respectively, adding up to 98% of total g variance. van der Maas et al. (2006) proposed that g may reflect the dynamic interaction between these processes rather than any specific process as such; the relative contribution of each process in this interaction may vary across different tasks, depending upon their specific demands (van der Maas, Kan, Marsman, & Stevenson, 2017). Thus, it is important to specify how each process relates with school performance at different phases of education.

1.1.2. Development

All processes above develop from birth to adulthood. Processing becomes faster with time (Demetriou et al., 2013; Kail et al., 2015). Attention becomes more efficient in focusing on stimuli for the time needed, in resisting distraction until processing is complete, and flexibly shifting between stimuli or responses according to needs (Arsalidou & Pascaul-Leone, 2016; Zelazo, 2015). Working memory increases so that more information may be held in mind and processed (Case, 1992; Pascual-Leone, 1970). The unit of representation changes from reality-referenced representations to relational constructs signifying relations at various levels of abstraction (Demetriou & Spanoudis, 2018).

Inference also changes at several levels. For instance, at preschool, representations function in blocks largely matching their episodic origin rather than inferential links. Toddlers may translate representational ensembles into reasoning sequences, which cannot yet justify: e.g., “uncle's car is outside, so he is in”. Later in preschool they induce similarity-based analogical relations and they may reason pragmatically, implementing reasoning schemes in realistic contexts: e.g., “You said I can play outside if I eat my food; I ate my food; I go to play outside” (Kazi et al., 2012). In primary school, representations are organized by rules, allowing systematic analogical reasoning (Sloutsky, 2010; Sloutsky & Fisher, 2004). Also, they demonstrate flexible deductive reasoning as captured by reasoning schemes, such as modus ponens, conjunction, and disjunctions (Moshman, 2015). In adolescence, rules are organized by principles which enable to grasp higher order abstract relations and systematically use reasoning to conceive of or uncover relations beyond the observable. Adolescents grasp the constraints of different inferential processes and they can ground inference on principles of truth and validity, resisting logical fallacies (Demetriou & Spanoudis, 2018; Moshman, 2015).

Cognizance is awareness of cognitive processes, including awareness of the mental origins of knowledge and problem solving, of procedural characteristics and demands of mental processes, and self-representations and self-evaluations. The development of cognizance reflects the cognitive processes emerging in each phase (Demetriou et al., 2018). In preschool, children become aware of their own and others' representations. For instance, they understand that representations and knowledge emerge from perceptions of objects. Thus, they acquire a Theory of Mind allowing them to understand that different persons may have different representations and beliefs because their perception of a situation was different (Wellman, 2014). In primary school, children may explicitly differentiate between mental processes, such as memory and inference and they may shift between them. For instance, they understand that to remember they need to observe carefully and rehearse (Chevalier, Martis, Curran, & Munakata, 2015; Paulus, Tsalas, Proust, & Sodian, 2014; Spanoudis et al., 2015). In adolescence, they become aware of inferential processes, such as deductive and inductive reasoning, and of the constraints underlying their validity (Demetriou et al., 2017; Moshman, 2015). Thus, with development, individuals become increasingly accurate in evaluating their performance and representing their own strengths and weaknesses. Overall, self-evaluations of performance and cognitive self-representations tend to reflect actual performance with relative accuracy since early adolescence, becoming increasingly stricter and less positive with attainment of principle-based reasoning (Demetriou et al., 2017; Demetriou, Makris, Kazi, Spanoudis, & Shayer, 2018; Demetriou & Spanoudis, 2018).

The developmental patterns outlined suggest that the nature of g varies in development. Specifically, the relation between reasoning and processing and representational efficiency changes with development. On the one hand, the relation with attention control (−0.52, −0.35, and − 0.17, at 9–11, 11–13, and 13–15 years, respectively) and flexibility (−0.71, −0.38, and − 0.10, for the three age groups, respectively) decreases with age, because these processes tend to automate with age; on the other, the relation with working memory (0.06, 0.65, and 0.74, for the three age groups, respectively) and awareness strengthens, because these processes develop until late adolescence (0.25, 0.30, and 0.35, for the three age groups, respectively). These patterns suggest a shift from executive processes related to attention control to reasoning processes and explicit awareness involved in problem solving and planning (Demetriou et al., 2017; Makris et al., 2017).

1.2. Intelligence, socioeconomic environment, and academic performance

School performance is related to cognitive ability. Psychometric intelligence accounts for about 30% of variance of school performance, although this relation may vary with level of education (Gustafsson & Balke, 1993; Roth et al., 2015). Also, academic self-concept (Guay, March, & Boivin, 2003; Johannesson, 2017), self-evaluation (Mabe III & West, 1982), cognitive self-representation, and personality (Demetriou, Kazi, Spanoudis, & Makris, 2019a, in press) relate with academic performance additionally to intelligence. This relation is mutual: academic performance beneficially influences cognitive ability, resulting into an increase of about from 1 to 5 IQ points for every additional year of schooling (Ceci, 1991; Gustafsson, 2008; Kyriakides & Luyten, 2009; Ritchie & Tucker-Drob, 2018). Understandably, schooling influences some cognitive processes, such as metacognition, more than others, such as processing speed (Van de Vijver & Brouwers, 2009).

Cognitive development and school learning occur in a cultural and social context. Socio-economic status of the family is a powerful factor of cognitive development and school achievement (Roazzi & Bryant, 1992). Many studies showed that poverty and low parental education are associated with lower levels of school achievement and IQ later in childhood. It is estimated that SES accounts for about 5% (Bradley & Corwyn, 2012) to 10% of school achievement variance (Sirin, 2005). There is less agreement about the source of these effects. Some authors argue that individual differences in SES relate to genetic differences associated with cognition (Belsky, Domingue, et al., 2018; Grasby, Coventry, Byrne, & Olson, 2017). According to this interpretation, school achievement differences between children from different SES groups are mediated by their genetically shaped cognitive differences. Figlio, Freese, Karbownik, and Roth (2017) disputed this interpretation, founding no evidence of SES mediation between genetic factors and test scores reflecting school success. An alternative interpretation would be that SES may not affect cognitive functioning as such, but it may directly affect school performance. For instance, initial disadvantage in family SES would affect attitudes or work habits related to school learning among higher SES individuals, regardless of actual cognitive potential. According to this interpretation, a middle or higher SES advantage implies availability of resources, motivation, and habits closer to school. In line with this interpretation, there is evidence that quasi-experimental changes in SES dimensions, such as an increase in family income, caused improvement in children's academic performance (Duncan & Magnuson, 2012).

These findings justify asking if different tasks at school require a different combination of mental processes to be mastered. It is also important to map the processes driving academic performance at different school grades or levels. That is, to specify if academic performance at different levels of school is driven by different cognitive processes, as these dominate in the cognitive developmental phase corresponding to the school level concerned. The design of the present study allows to test these alternative predictions about the source of these effects.

1.3. Predictions

We addressed the following processes: (i) processing efficiency and executive control; (ii) working memory; (iii) reasoning; (iv) language; and (v) self-evaluation of performance on reasoning tasks. School grades in three school subjects, mathematics, science, and Greek, were obtained from participants' schools. Thus, we tested how each process relates to school performance in primary and secondary school. Therefore, this study may help disentangle the influence of different cognitive, language, and metacognitive processes on school performance more precisely than it has been possible by earlier studies focusing separately on each of these factors. It may also show how these influences may change in development. Based on the literature summarized above, the following predictions may be tested:

1. The hierarchical structure of the processes involved must be present at both the level of each realm examined (i.e., processing and representational efficiency, reasoning, and cognizance) and all of them together. Thus, it is predicted that a model involving both *the specific processes* in each realm (i.e., processing speed, attention control, flexibility, and working memory in the realm of processing efficiency; rule-based and principle-based reasoning and language in the realm of thought processes, and rule-based and principle-based cognizance in cognizance) and the *realm-specific general factor* would be superior to a model involving only the general factor in each realm. Validating this model is needed for the specification of the relations between the various processes and academic performance.
2. Overall, reasoning and language ability would dominate as predictors of school achievement over efficiency and cognizance processes because they are more directly involved in ongoing learning at school (McDermont, Mordell, & Stoltzfus, 2001).
3. However, the developmental model outlined above suggests a principle of developmental relativity in the predictive power of different mental processes. Specifically, in each developmental phase, the processes under formation in this phase are the best predictors of academic performance, because they represent the state of mental functioning better than previously well-formed or still unformed processes. Therefore, in primary school, executive processes, such as mental flexibility and working memory, must be better predictors than reasoning, language and cognizance. Additionally, these processes may be more relevant for learning in primary school because they reflect the ability to conform to school demands and demonstrate the effort and focus needed to master the concepts and skills taught at this level of education. In secondary school, reasoning, language, and cognizance would dominate as predictors. On the one hand, their acquisition culminates in early adolescence: principle-based reasoning is established, the underlying semantic, syntactic, and grammatical aspects of language are mastered, and cognizance becomes accurate in self-evaluation and self-representation. On the other hand, the concepts and skills taught at this level of education are more abstract and require more self-understanding and self-regulation.
4. Two alternative predictions were tested about SES. (i) The cognitive mediation hypothesis claims that SES differences in school achievement are mediated by cognitive differences. (ii) The direct effect hypothesis states that SES directly influences school achievement rather than mediated by cognitive ability.

2. Method

2.1. Participants

Participants (N = 196) were drawn among third (N = 54, 25 male; mean age = 8.56, SD = 0.35, range 7.92–9.50), fifth (N = 44, 26 male; mean age = 10.71, SD = 0.59, range 9.33–12.08) (primary school), seventh (N = 53, 26 male; mean age = 12.65, SD = 0.43, range 12.08–14.75), and nineth grade (N = 45, 25 male; mean age = 14.62, SD = 0.33, range 14.17–16.00) (secondary school) of compulsory education. These participants lived in Alexandroupolis and Veria, cities in nothern Greece. They were all Greek and native speakers of Greek and representative of the general population, although representation of middle class families was relatively higher than in the general population (42% of children's parents in the present sample had university education as contrasted to 25% of total population). SES was scored as low (1, parents with no more than complulsory education, 26% of the sample), lower middle (2, parents with secondary education, 32% of the sample), and upper middle class (3, at least one parent with university education, 42% of the sample).

2.2. Task batteries

2.2.1. Processing efficiency tasks

A series of Stroop-like tasks measured speed and attention control under three symbol systems (i.e., verbal, numeric, and visual) (Demetriou, Christou, Spanoudis, & Platsidou, 2002). Specifically, there were 36 stimuli for each symbol system, 18 congruent stimuli addressed to speed and 18 stimuli incongruent addressed to attention control.

For verbal speed of processing, participants read color words denoting a color written in the same ink-color (e.g., the word "red" written in red). For verbal control, participants recognized the ink-color of color words denoting another color (e.g., the word "red" written in blue ink). In the number domain, several "large" number digits (e.g., 4, 7, and 9) were composed of the same or a different "small" digit (i.e., 7 composed of little 7 s or 4 s). For speed, participants recognized the large congruent numbers. For attention control, participants recognized the component number of incongruent numbers. In picture recognition, several large geometrical figures (circles, triangles, and squares) were made up of the same (congruent) or a different (incongruent) figure. For speed, participants recognized the large geometrical figure of congruent conditions; for attention control, they recognized the small figure of incongruent conditions (Cronbach's alpha was 0.93). Six mean scores were computed for these tasks. Three symbol-specific scores on compatible tasks stood for processing speed. Three symbol-specific scores on the incompatible tasks stood for attention control.

2.2.2. Short-term and working memory

Three computer-administered tasks examined working memory (Demetriou et al., 2002). The verbal and the numerical tasks addressed forward word and 2-digit forward number span, respectively. There were six levels (2–7 units) with two sets in each level in each system. The visuo/spatial working memory task required to store shape, position, and orientation of geometrical figures. Participants were presented several arrangements of geometrical figures and had to fully reproduce them by choosing the appropriate figures among several ready-made arrangements identical in size and shape to the figures drawn on the target cards. A score for each task reflected the higher level attained, credited if at least one of the sets addressed to this level was successfully performed. Cronbach's alpha was 0.49. Although rather low, the reliability of these tasks was in the range expected for tasks addessing different aspects of working memory (Conway, Kane, Hambrick, & Engle, 2005). Using these scores in latent variable models largely compensates for this weakness (Bentler, 2006).

2.2.3. Cognitive flexibility

Two tasks addressed cognitive flexibility. In the first, a series of Stroop-like tasks were used. As above, these tasks were given under the verbal, numeric, and visual symbol system (a total of 50 incongruent stimuli for each symbol system were used). Depending on two rules (main and minor rule), participants were required to recognize out loud one or another dimension of the stimuli presented. Forty stimuli were recognized based on the main rule (e.g., color, large number, and geometrical figure for the verbal, the numerical and the figural cognitive flexibility task, respectively); the remaining 10 were recognized on the basis of a second (minor) rule (e.g., the word, the small number figure, the small geometrical figure for the verbal, numerical and figural cognitive flexibility task, respectively). Thus, when the rule changed across successive trials, participants had to shift from the one (e.g., color, large figure) to the other dimension (word, small figure) of the current stimulus and vice versa. The main and the second (minor) rule changed across the participants. The 50 trials in each of the three tasks were presented in a pre-randomized order. The crucial variable was mean RTs in the trials requiring shifting from the main to the minor rule one.

The second was the Visually Cued Color-Shape Task (VCCST) used by Zelazo et al. (2004). Participants saw a screen showing a row of four target items (a red triangle, a green circle, a blue square, and a yellow diamond). They had to sort several test items presented at the center of the screen beneath the target row, by color or shape, indicated by a symbol prescribing if the item must be sorted by color (X) or shape (Y). Two 50-item sets were created; in the first, 40 test items were indexed by X (color) and 10 by Y (shape); in the second, 40 items were indexed by Y and 10 by X. The Y items in the first set and the X items in the second were distributed randomly throughout the 50 trials. Half of the children (randomly) took the one set and the rest took the other set. When a sorting error occurred, the item remained on screen until the correct key was pressed. Perseverative and non-perseverative errors were counted as scores for shifting. Perseverative responses are correct under the other rule; all other errors are non-perseverative. Cronbach's alpha was 0.72.

Five scores were computed for flexibility in shifting. Three for performance on the Stroop-like task (one for each symbol-system) and two for performance on the VCCST task, one for perseverative and one for non-perseverative errors.

2.2.4. Reasoning and problem-solving tasks

The tasks addressed to each domain were selected from a battery of cognitive development that is well validated (Demetriou & Kazi, 2001, 2006; Demetriou & Kyriakides, 2006; Demetriou, Mouyi, & Spanoudis, 2008). Detailed information about the psychometric properties of the full test from which tasks were drawn for the present purposes are presented in Demetriou and Kyriakides (2006).

2.2.4.1. Inductive and deductive reasoning. For inductive reasoning, children solved four verbal analogies of the a: b:: c: d type where one or two of the terms would have to be chosen among three alternatives. First to 4th order analogies were used standing for the two levels of rule-based (e.g., bed: sleep:: - [paper, *table*, water]: — [*eating*, rain, book]) and principle-based thought (e.g., {(tail: fish:: feed: mammals)::: - [*movement*, animals, vertebrates]}:::: {(propeller: ship:: wheels: car)::: - [vehicles, *transportation,* carriers]}). For deductive reasoning four tasks addressed 1st, (i.e., if p > q and p > r, what is correct, q > s, p > s, or none) and 2nd level rule-based (i.e., if p then q, not q, therefore not p) and 1st level (if p > q and r < s, what is correct, r > p, r < r < p, or none) and 2nd level principle-based reasoning (if p then q, q, what is correct, not p, p, or none).

2.2.4.2. Quantitative reasoning. Arithmetic, numerical analogical reasoning, and algebraic reasoning were examined. For numerical reasoning, children specified the missing operation in four problems (i.e., (9 * 3) = 6; [(2 $ 4) # 2 = 6]; [(3 $ 2 * 4) ^ 3 = 7]; [(3 $ 3) # 1 = (12 $ 3) * 2]) addressed to early and late rule-based thought and early and late principle-based thought, respectively. Numerical analogical reasoning involved seven mathematical analogies addressed to 1st (6: 12:: 8:?) and 2nd level rule-based (6: 8:: 9:?;) and 1st (6: 4:: 9:?) and 2nd level principle-based proportional reasoning (i.e., participants specified which of the six items above involved the same relation with (24: 16:: 12: 8)).

2.2.4.3. Causal reasoning. Combinatorial thinking and hypothesis testing tasks addressed causal (scientific) reasoning. For combinatorial thinking, participants specified all possible combinations of drawing sets of balls of increasing color variability out of a box (e.g., two red and a green ball; a blue, a red and green ball, etc.), tapping the four levels of rule-based and principle-based reasoning. Hypothesis testing was addressed by a task requiring isolation of variables for testing hypotheses of increasing complexity (e.g., participants had to choose the right combination of weights and engines in designing a truck to test how weight affects the speed (1 × 2, 2 × 2, and 2 × 2 × 2)) variables had to be manipulated to test the hypotheses involved.

2.2.4.4. Spatial reasoning. Five tasks addressed mental rotation, visualization, and coordination of perspectives. For mental rotation, participants drew how various geometrical figures would appear if rotated by 45, 90, or 270 degrees; also, they had to specify the three-dimensional object to come by rotating each of three letters (H, Ψ, and P) around their vertical axis. One- and two-dimensional figures in the first task addressed first- and second-phase rule-based thought. The *letters* task required principle-based reasoning because the participant must project a two-dimensional picture (the letters) into a three-dimensional mental image and map this mental image onto a two-dimensional token of it. These tasks were scored on a pass-fail basis and were summed for the needs of modelling. Cronbach's alpha was 0.83.

Having systematically addressed to developmentally ordered levels of reasoning across domains, this battery is a developmental test of fluid intelligence (Gf). To examine possible differences in the relations between successive developmental levels of Gf and academic achievement, performance on rule-based tasks were combined into one score and performance on principle-based tasks were combined into another score, in each domain.

2.2.5. Self-evaluation

Two types of self-evaluations were obtained. Specifically, after solving each of the cognitive tasks above, participants were asked to evaluate (i) their performance ("How right do you think your solution on this task was?") and (ii) the difficulty of the task ("How difficult this task was for you?") using a five-point scale (i.e., Not (successful, difficult) at all … (5) very (successful, difficult)). Success evaluations represents the evaluative aspect of cognizance which enables one to monitor performance vis-à-vis cognitive goals and regulate problem solving attempts. Difficulty evaluations represents the ability to monitor task demands and regulate problem solving relative to its mental cost (Cronbach's alpha for success and difficulty evaluation was 0.93 and 0.91, respectively). To relate these scores with actual performance their Euclidean distance was calculated. For each pair of task performance and success or difficulty evaluation Euclidean distance was evaluated after they were transformed into z scores to ensure comparability. Euclidean distance is the root of square differences between a pair of scores.

2.2.6. Language

To test language ability, several tasks addressed vocabulary, syntax, and semantics. This battery was developed as a test of language proficiency in Greek and was validated in a large sample representative of children from 8 to 14 years of age. It addresses morphological, syntactic and semantic processes and is used as a diagnostic tool for language disabilities. For vocabulary, (i) children specified 13 words whose first phoneme and definition was given (e.g., fr … means a person whom we love), (ii) defined 13 words (e.g., "What is a bed?") and (iii) answered the Greek version of the vocabulary test in WISC-III. For syntax, children spotted the grammatical/syntactical mistakes in 15 sentences (e.g., "Three friends takes the spoon"), organized sets of scrambled words into syntactically acceptable sentences (e.g., child, tree, climbs, the, onto), and changed the verbs appearing in short stories from present to past term. For semantics, children combined simple sentences into more complex semantically coherent sentences (e.g., "I am old" and "I am tall" into "I am old and tall"), arranged scrambled sentences into meaningful stories and answered questions probing understanding of the gist of a story. Three mean scores (i.e., vocabulary, oral, and written language) were used in models involving a single language factor. The reliability of performance on all language tasks was very high (Cronbach's alpha was 0.92). The reliability of each of the three scales was also high: Cronbach's alpha was 0.79, 0.80, and 0.84, for vocabulary, syntax, and semantics, respectively.

2.2.7. Academic performance

School grades of academic performance in three school subjects, Greek, mathematics, and science, were obtained from schools. School grades in the Greek system reflect both teachers' evaluation of performance in the classroom and performance on written assignments or tests in each subject. The grade scale differs between primary and secondary, varying from 1 to 10 in primary school and 1 to 20 in secondary school. Finally, first grade children of secondary school did not have grades in science because this subject is not taught at this grade. To ensure comparability, in the models below, these scales were standardized within each education level. Reliability was very high: Cronbach's alpha was 0.98.

2.3. Procedure

All participants were tested individually at school, by the same experimenter, in four 45 min sessions, including (i) all speeded performance, shifting, and working memory tasks, (ii) the cognitive tasks, (iii) the oral language tasks and WISC-III vocabulary, and (iv) the written language tasks. Sessions were randomized across participants.

3. Results

3.1. Rationale of modelling, statistical power, and general patterns of performance

Structural equation modelling was used to establish the robustness of cognitive factors involved in each realm of processes and disentangle their influences on academic performance. Specifically, three sets of models were first tested within each realm of processes: In the first model, only one common factor was associated to all measures in the realm. In the second model, domain-specific factors were added, one for each of the domains represented in each realm; these factors were regressed on a second-order general factor, standing for the realm. Comparing the second to the first model allows to examine if only one factor would suffice to account for performance in the realm concerned or if, additionally, the domain-specific factors are also needed. Therefore, these two sets of models aimed to test the first prediction. In the third model, academic performance was also involved. Academic performance was regressed on the general and the domain specific factors; this manipulation allows testing how each of the factors in a realm relates with cognitive performance independently of the other realms. In a fourth model, all three realms were included in a common model, as shown in Fig. 2. This model allows to test the relation of each processes disentangled from possible influences from other realms. Therefore, these models aimed to test the second prediction. This last model was also tested in several two group-analysis models involving the primary and the secondary school students. Also, alternative cascade models, where the general factor was dropped in favour of direct relations between the factors, were tested to zoom on in the direct relations of each process to academic performance. Therefore, these models tested our third prediction about possible differences between school levels in the relations between cognitive processes and academic performance. The last prediction about SES influences was tested in several of these models as explained below.

A series of a priori power analyses for testing data-model fit examined how many participants would be needed to achieve a desired level of power (0.80). Power analyses were performed using MacCallum–Browne–Sugawara (MBS) method (MacCallum, Browne, & Sugawara, 1996). Our estimation was based on Preacher and Coffman (2006) on-line utility for RMSEA based sample size computation. We tested all SEM models using exact fit hypothesis using $\alpha = 0.05$, $e0 = 0.05$ and $e1 = 0.02$ (Kim, 2005); all power analyses yielded a minimum sample size to detect effect between 59 and 168 participants. Therefore, our sample is appropriate for testing the models below on the level of the total sample and the group level contrasting primary to secondary school students.

It is noted that in all models including the whole sample, the general academic performance factor was identified in reference to all three school subjects described above, resulting in dropping the first secondary school grade where science was not measured ($N = 20$). To preserve this grade in 2-group models comparing primary with secondary school participants, in sake of statistical power, the general academic performance factor in secondary school was defined in reference to language and mathematics which were available. Thus, total sample models were estimated on 178 participants; 2-group models involved 98 participants in each group. Thus, all models were well within the power requirements as specified above.

Fig. 1 shows standardized attainment on the main dimensions involved in the various models as second-order factors. Table 1 presents the correlations between these dimensions. Fig. 1 shows that all cognitive dimensions increased systematically across school grades, $F_{3,184} = 71.87$, $p < .0001$, $\eta_p = 0.56$, and across SES levels (not shown in Fig. 1), $F_{2,184} = 15.61$, $p < .0001$, $\eta_p = 0.16$. The significant grade x cognitive dimension interaction, $F_{6,182} = 12.97$, $p < .0001$, $\eta_p = 0.32$, indicated that change with grade varied across cognitive dimensions. Table 1 shows that all correlations between the cognitive dimensions were significant and some of them were very high. Academic performance correlated significantly with SES and all cognitive dimensions but attention control. The statistics and correlations between the individual measures involved in the various models are presented in Supplementary Tables.

3.2. Realm-specific models

3.2.1. Processing efficiency

The model tested on processing efficiency involved the following measures: the processing speed factor represented by the three symbol-specific compatible measures; the attention control factor was represented by the corresponding incompatible measures; the flexibility factor was represented by the three Stroop-like and the two VCCST measures standing for flexibility; the working memory factor was represented by the three working memory measures. In the first model, all scores were related to a common general factor that stands for processing efficiency. It can be seen in Table 2 that the fit of this model was poor. The second model involved a domain-specific factor for each of the four processes (speed, attention control, flexibility, and working memory) which were regressed on a common second-order factor. The fit of this model was much better than the single g-factor model (see Table 2). In the third model, which was better than the second model above (see Table 2), academic performance was regressed on the general factor and also on the *residuals* of flexibility and working memory (academic performance was not regressed on speed and attention

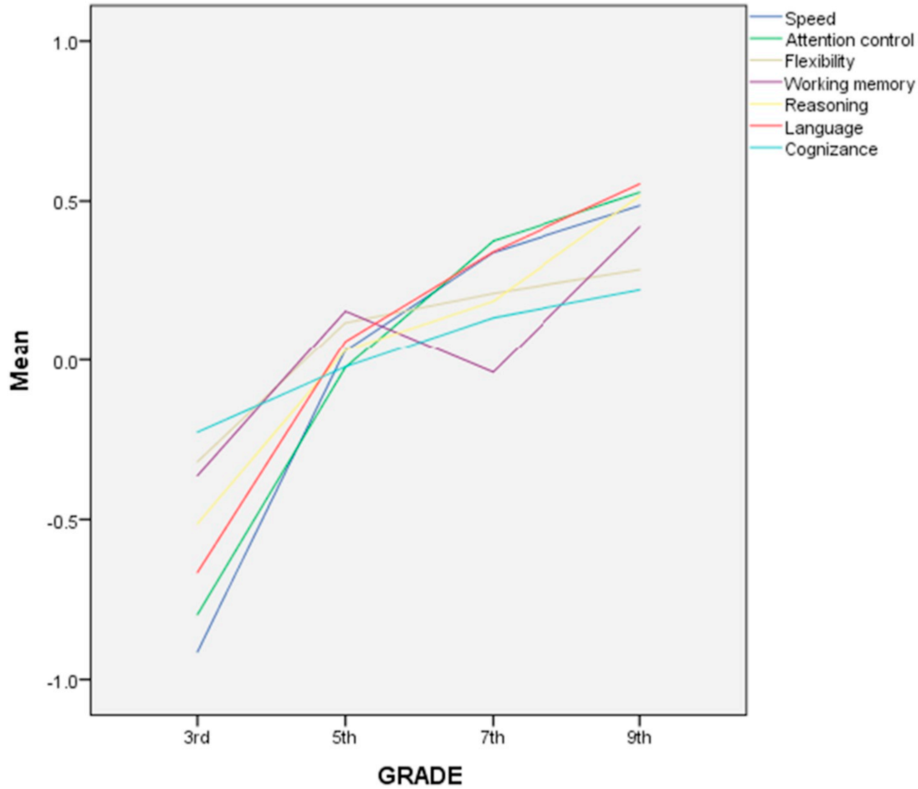

Fig. 1. Mean z score across all main cognitive dimensions as a function of school grade. Note. Speeded performance scores (speed, attention control, and flexibility) were inverted to facilitate comparison with the rest.

control because these factors were completely absorbed by the general factor). In this fashion, the model shows how each specific process relates with school performance, on top of its relation with the higher-order common factor. This model was better than both models above (see Table 2). The relation between general processing efficiency and academic performance was moderate but significant (β = −0.20).

3.2.2. Reasoning and language

Reasoning was represented by the two scores standing for performance on rule-based and the two scores standing for performance on principle-based reasoning. Language was represented by the three language measures. In the fashion above, in the first model, scores were related to a common general factor that stands for reasoning and linguistic ability; the second model involved a domain-specific factor for each domain (rule-based reasoning, principle-based reasoning, and language) which were regressed on a common second-order factor. The fit of the second model was significantly better than the first model (see Table 2). In the third model, academic performance was regressed on the common factor and the residual of language; the residuals of rule-based and principle-based reasoning were not included because their relation with the general factor was very high (β > 0.9) leaving no reliable residual to be used as predictors. This fit of this model was relatively weaker than the second model above but acceptable. The relation of academic performance with the general reasoning-language factor was moderate but significant (β = 0.20) but the relation with language (β = 0.83) was very high.

3.2.3. Cognizance

Cognizance was represented by the self-evaluation scores on the corresponding rule-based and principle-based tasks. In the first model, all four scores were related to a general cognizance factor; in the second model, the rule- and the principled-based scores were related to separate level-specific factors which were related to a second-order cognizance factor. The second model fit much better than the first (Table 2). In the third model, academic performance was regressed on the general cognizance factor (β = 0.19) and the residual of the principle-based

Table 1
Correlations between age, SES, cognitive processes, and general academic performance.

Processes	1	2	3	4	5	6	7	8	9	10
1. Age	1.0									
2. SES	−0.11	1.0								
3. Speed	0.50	0.18	1.0							
4. Attention	0.55	0.09	0.91	1.0						
5. Flexibility	0.39	0.12	0.19	0.25	1.0					
6. WM	0.36	0.17	0.20	0.20	0.36	1.0				
7. Reasoning	0.52	0.20	0.41	0.38	0.41	0.41	1.0			
8. Language	0.62	0.22	0.51	0.49	0.57	0.54	0.68	1.0		
9. Cognizance	0.37	0.09	0.30	0.26	0.25	0.23	0.61	0.48	1.0	
10. GAP	−0.10	0.44	0.22	0.14	0.24	0.31	0.30	0.47	0.23	1.0
Mean			0.00	0.00	0.00	0.00	0.02	0.01	0.00	−0.03
SD			1.0	0.86	0.67	0.76	0.70	0.76	0.45	0.94

Table 2
Relations between first- and second-order factors in the model tested on the total sample (SE in parenthesis) and fit statistics of the models tested within each realm of processes.

	Second-order factors			
Realms	G	GAP in realm-specific models	GAP in the common model	age
Common model				
g			**0.541** (0.541)	
Model Fit $\chi^2(506) = 807.33$, CFI = 91, SRMR = 0.106, RMSEA =0.053, AIC = −0.204.66				
Processing efficiency				
gPRE		−0.200 (0.248)	—	−**0.595** (0.009)
Speed	1.00 —	—	—	
Attention control	—**1.00** (0.062)	—	—	
Flexibility	−**0.591** (0.314)	−0.144 (0.085)	—	
Working memory	−**0.398** (0.174)	**0.322** (0.192)	0.151 (0.133)	
Model fit				
Only g: $\chi^2(78) = 486.840$, CFI = 0.640, SRMR = 0.187, RMSEA = 0.165, AIC = 330.840				
Hierarchical: $\chi^2(74) = 225.23$, CFI = 0.87, SRMR = 0.08, RMSEA = 0.103, AIC = 77.225, $\Delta\chi^2(4) = 261.615$, $p < .001$				
GAP: $\chi^2(128) = 274.239$, CFI = 0.900, SRMR = 0.091, RMSEA = 0.087, AIC = 18.239				
Reasoning and Language				
gF		**0.198** (0.289)	—	**0.745** (0.008)
Reasoning Rule	**0.966** (0.303)	0.414 (1.325)	—	
Reasoning Principles	**0.913** (0.313)	0.316 (0.512)	—	
Language	**0.908**—	**0.830** (1.353)	**0.564** (1.444)	
Model fit				
Only g: $\chi^2(26) = 91.679$, CFI = 0.934, SRMR = 0.047, RMSEA = 0.115, AIC = 39.679				
Hierarachical: $\chi^2(22) = 45.89$, CFI = 0.98, SRMR = 0.037, RMSEA = 0.075, AIC = 1.89, $\Delta\ \chi^2(4) = 45.786$, $p < .001$				
GAP: $\chi^2(57) = 142.245$, CFI = 0.941, SRMR = 0.067, RMSEA = 0.099, AIC = 28.245				
Cognizance		**0.190** (0.169)	—	**0.432** (0.016)
gCOGN		—	—	
Cognizance Rule	1.00—	−0.018 (0.124)	—	
Cognizance Principle	0.114 (0.127)			
Model fit				
Only g: $\chi^2(9) = 251.94$, CFI = 0.498, SRMR = 0.232, RMSEA = 0.372, AIC = 233.940				
Hierarchical: $\chi^2(7) = 24.022$, CFI = 0.965, SRMR = 0.032, RMSEA = 0.112, AIC = 10.022, $\Delta\chi^2(4) = 227.918$, $p < .001$				
GAP: $\chi^2(31) = 52.06$, CFI = 0.973, SRMR = 0.062, RMSEA = 0.068, AIC = −9.094				
School				
Mathematics	**0.900**			
Science	**0.904**			
Greek	**0.913**			
SES	**0.315** (0.027)		**0.461** (0.081)	
AGE	**0.774** (0.013)			

Significance: $p < .05$. Coefficients equal to 1 not shown in bold were fixed to 1 for identification purposes.

factor ($\beta = -0.02$) (the rule-based residual was 0); the first of these relations was significant.

Therefore, in line with the first prediction, the models above suggested that all three realm-specific general factors and the domains tested in each realm were identified by this study. Also, in line with the second prediction, all general factors were significantly related with academic performance. Of the various domain-specific factors, only working memory and language survived to be used as autonomous predictors of academic performance. Thus, it is important to specify if these relations survive in a common model where the general factor, G, runs through all three realms, on top of the realm-specific general factors.

3.3. The common model

In sake of this aim, all three models above were integrated into a common model. In this model, the three realm-specific second-order general factors were related to a common third-order G factor. Academic performance was regressed on this factor and the residuals of the three realm-specific general factors. The fit of this model was good, (χ^2 (444) = 713.32, CFI = 0.92, RMSEA = 0.063 (0.054–0.071), AIC = −174.315). Only the relation between G and academic performance was significant ($\beta = 0.44$). Note that the amount of variance in academic performance accounted for by this factor (19%) was almost the double of the sum of the variance accounted for by the three realm-specific general factors (11%). This is a classic finding: the broader the g the better for predicting life outcomes (Gottfredson, 2002; Jensen, 1998). Being non-significant, the residuals of all three realm-specific general factors were dropped in a next model; in this model, academic performance was regressed on G and the residuals of two domain-specific factors which appeared to stand out individually in the realm-specific models above, namely working memory and language. The fit of this model, (χ^2 (445) =694.33, CFI = 0.92, RMSEA = 0.061 (0.052–0.069), AIC = −195.657) was better than the model above. In this model, the effect of g ($\beta = 0.34$) and language ($\beta = 0.47$) were significant but the effect of working memory was not ($\beta = 0.14$).

To test the possible involvement of SES, two variations of this model above were tested, which included age and SES. Specifically, in the first variation, g was regressed on age and SES, and GAP was regressed on g, working memory and language, (χ^2 (507) = 846.58, CFI = 0.90, RMSEA = 0.088 (0.058–0.074), AIC = −167.423). The effect of age ($\beta = 0.84$) and SES on GAP ($\beta = 0.17$) were significant. There was only one single difference between the first and the second variation: in the second, GAP was also regressed on SES. Thus, the first model shows the indirect effect of SES on GAP as mediated by g. The second shows if SES has a direct effect on GAP going beyond the indirect effect mediated by g. The fit of this model was better than the first, (χ^2 (506) =807.33, CFI = 0.91, RMSEA = 0.053 (0.054–0.070), AIC = −204.66; $\Delta = \chi^2$ (1) = 39.243, $p < .001$). This is the model shown in Fig. 2. This

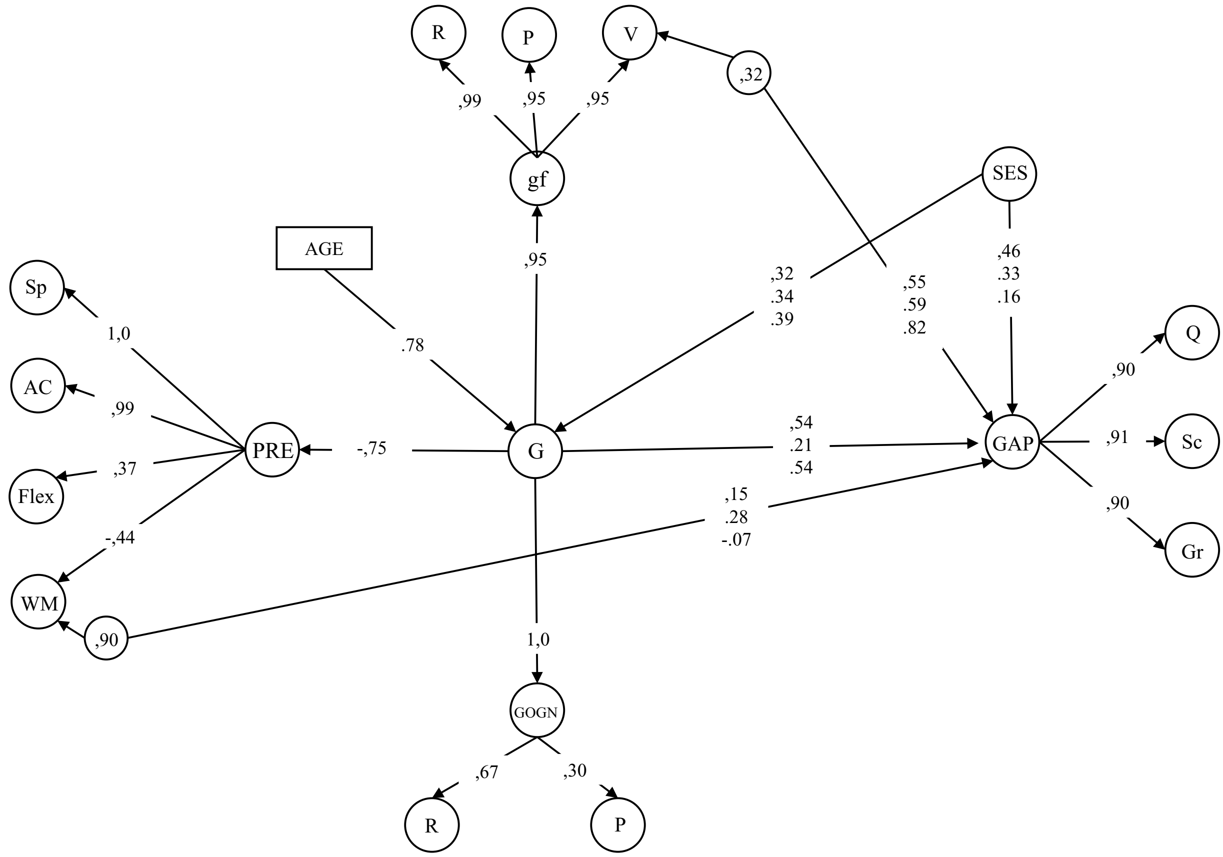

Fig. 2. The general model tested within each of the four realms and also the common model testing relations across realms. Note: Structural relations are shown for the total sample (first value of each triad), primary school (second value of each triad), and secondary school students (third value of each triad). The symbols R and P stand for rule-based and principled-based reasoning (gf) or cognizance (COGN); the symbol V stands for verbal ability. The symbols Sp, AC, Flex, and WM stand for speed, attention control, flexibility, and working memory, respectively. The symbols M, Sc, Gr, and GAP stand for mathematics, science, Greek, and General Academic Performance, respectively.

difference reflected the fact that the indirect effect of SES on GAP was very small and non-significant ($\beta = 0.04$); in the second model, the direct effect of SES on GAP was high and significant ($\beta = 0.46$); when all cognitive factors and lnagugae were regressed on SES, the cumulative indirect effect on GAP was stronger but still relatively small ($\beta = .12$) and the direct still moderately strong ($\beta = .33$); also, the effect of both age ($\beta = 0.78$) and SES ($\beta = 0.32$) on g was significant. Notably, these relations did not basically affect the relations of GAP with the other factors. In fact, in this model all relations were significant ($\beta = 0.54$, $\beta = 0.15$, and $\beta = 0.55$ for g, working memory, and language, respectively). It is noted that these relations were minimally (and non-significantly) affected when the model was tested after partialling out the effect of age on each of the measures involved (χ^2 (476) = 705.79, CFI = 0.93, RMSEA = 0.056 (0.047–0.065), AIC = −246.21; $\beta = 0.45$, $\beta = 0.17$, and $\beta = 0.58$ for g, working memory, and language, respectively). Therefore, in line with prediction 4ii, SES directly affects school performance additionally to any effects that it may exert on cognitive ability.

To test the possible differences between school subjects, a model was tested where the GAP factor was abolished and each of the school three subjects was independently related to the factors above (g, working memory, language, and SES). No difference was found.

3.3.1. Developmental changes in cognition-academic performance relations

To test the third prediction about possible differences between primary and secondary school students, the model shown in Fig. 2 was tested in a 2-group analysis involving the primary school students in one group and the secondary school students in another. Due to the lack of science grades at the first grade of secondary school, the general academic performance factor in the secondary school group was defined only in reference to performance in Greek and mathematics. In this model, all measurement-factor relations and relations between first and second order factors were constrained to be equal across the two groups; the relations between predictors and school performance were free to vary between the two groups. Therefore, this model assumes that the various factors were similarly identified in the two groups but the relations between predictors and academic performance may differ between levels of education. The fit of this model was excellent, (χ^2 (1007) = 0.44, CFI = 1.0, RMSEA = 0.00, AIC = −2013.56). The relation between G and academic performance in primary school ($\beta = 0.30$) was significant but significantly lower than in secondary school, ($\beta = 0.46$, $z = 1.70$, $p < .05$); the relation of academic performance with working memory in primary school was also significant ($\beta = 0.28$) but significantly lower than in secondary school, where this relation was non-significant, ($\beta = -0.16$, $z = 2.21$, $p < .01$). The relations of academic performance with language ($\beta = 0.57$) and ($\beta = 0.59$) and SES ($\beta = 0.32$ and $\beta = 0.26$) were significant and very similar in the two school levels.

To further decompose these relations, the higher-order factors were abolished and cascade relations between the first-order factors were imposed in their place. Specifically, to simplify the model, the speed factor was abolished; the attention control factor was regressed on age; flexibility was regressed on attention control; working memory was regressed on flexibility; rule-based reasoning was regressed on working memory; principle-based reasoning was regressed on rule-based reasoning; language was regressed on rule-based reasoning; rule-based and principle-based cognizance were regressed on their corresponding reasoning factors. GAP was regressed on attention control and the

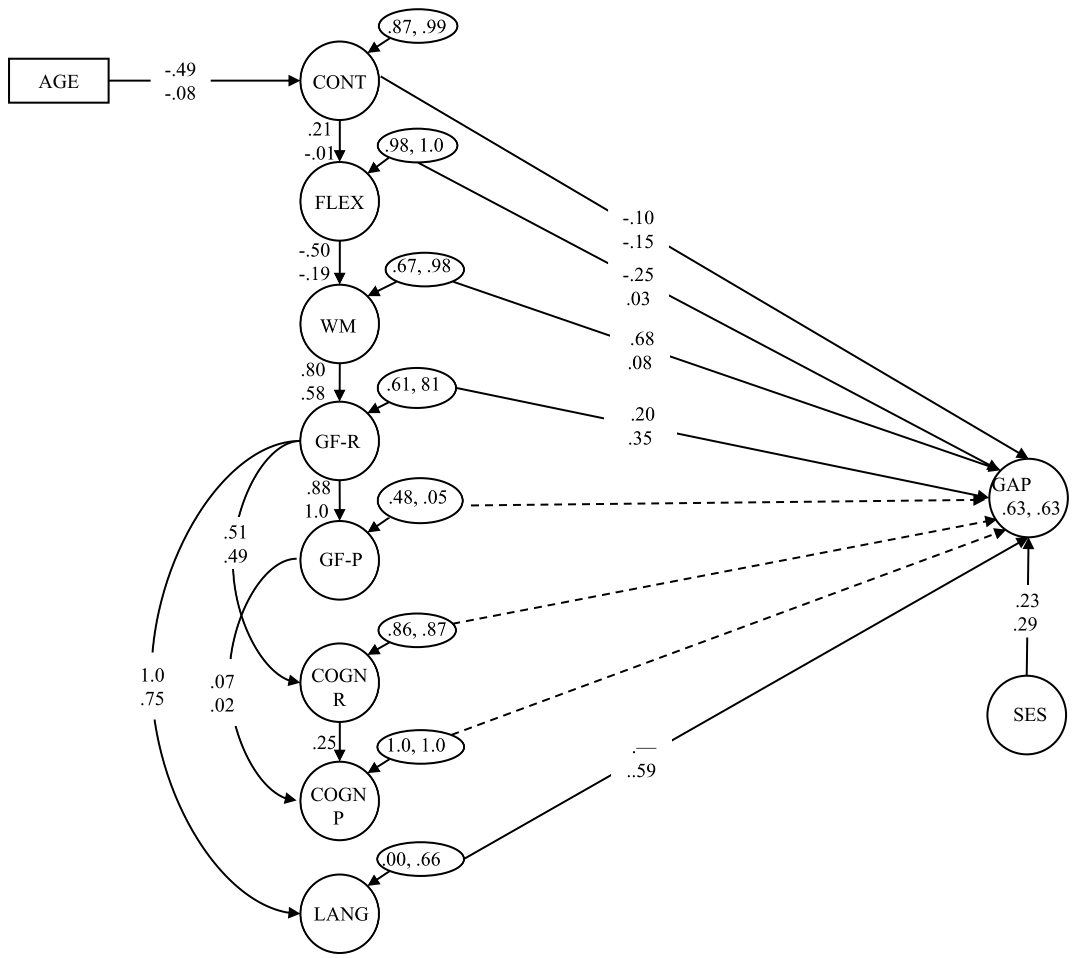

Fig. 3. Structural relations between the factors involved in the cascade model tested in a two-group model including the primary and secondary school students (first and second number of each pair, N = 98 in both groups).

residuals of all other factors with a structural relation with another factor that was lower than 0.9, to avoid specifying relations based on very low variance. The fit of this model was also excellent, Sattora-Bentler robust (χ^2 (818) = 2.89, CFI = 1.00, RMSEA = 0.00, AIC = −1633.11). This is the model shown in Fig. 3. The pattern of relations between GAP and the various cognitive factors was very different in the two groups. In primary school, the relations with flexibility (β = −0.25), working memory (β = 0.68), and SES (0.23) were significant; in secondary school, the relations with rule-based reasoning (β = 0.43), language (β = 0.59) and SES (β = 0.29) were significant. Therefore, in primary school, executive processes are the dominant predictors of academic performance; in secondary school, there is a shift towards inferential processes and sheer language ability, probably reflecting the emergence of crystallized processes as a component of school performance. The implications of these findings will be discussed further in the discussion.

3.3.2. Focusing on cognizance

Cognizance was the weak link in the models above. All other processes appeared to relate with each other and influence, one way or another, academic performance. Cognizance appeared to have a weak relation with academic performance in the model focusing on this realm; however, it was completely masked by other processes in the integrated models, creating the impression, against the fourth prediction, of a redundant construct. To further probe its role, if any, several models focusing on cognizance were tested in two-group analyses involving the two levels of education. The first model included only flexibility, cognizance, and academic performance measures, as described above. In this model, a cascade was built where rule-based cognizance was regressed on flexibility and principle-based cognizance was regressed on rule-based cognizance; academic performance was regressed on flexibility and the residuals of the two cognizance factors. Flexibility was selected to be included in this model for two reasons. First, flexibility requires effortful attention control to ensure faultless shifting; at the same time, it is simple enough to allow registering errors when happening. Second, flexibility was shown in the models above to clearly differentiate the two school level groups. Thus, one might assume that flexibility would be associated with cognizance in primary school, when flexibility is in the process of formation, but not in secondary school, when this type of flexibility is automated. However, only in secondary school, cognizance would be related to academic performance, when it reaches a certain level of precision. This is precisely what this well-fitting model showed, Satorra-Bentler scaled (χ^2 (135) = 138.61, CFI = 0.99, RMSEA = 0.007, (0.00–0.049), AIC = −134.40). In primary school, cognizance was significantly predicted by flexibility (β = −0.24) but it did not predict GAP (β = 0.13 and β = 0.13 for rule- and principled based cognizance, respectively). In secondary school, cognizance was not predicted by flexibility (β = −0.16); however, rule-based cognizance did (β = 0.25) but principle-based cognizance did not predict GAP (β = −0.13). Obviously, when mental flexibility is still under formation, in primary school, it generates awareness; later, when automated, it submerges below awareness. However, when established, it is predictive of school performance, probably because it contributes to learning in school, although it may be masked by cognitive measures, if present.

Fig. 4 illustrates the relations captured by the models above. Specifically, Panel A of Fig. 4 shows the relations between mean academic

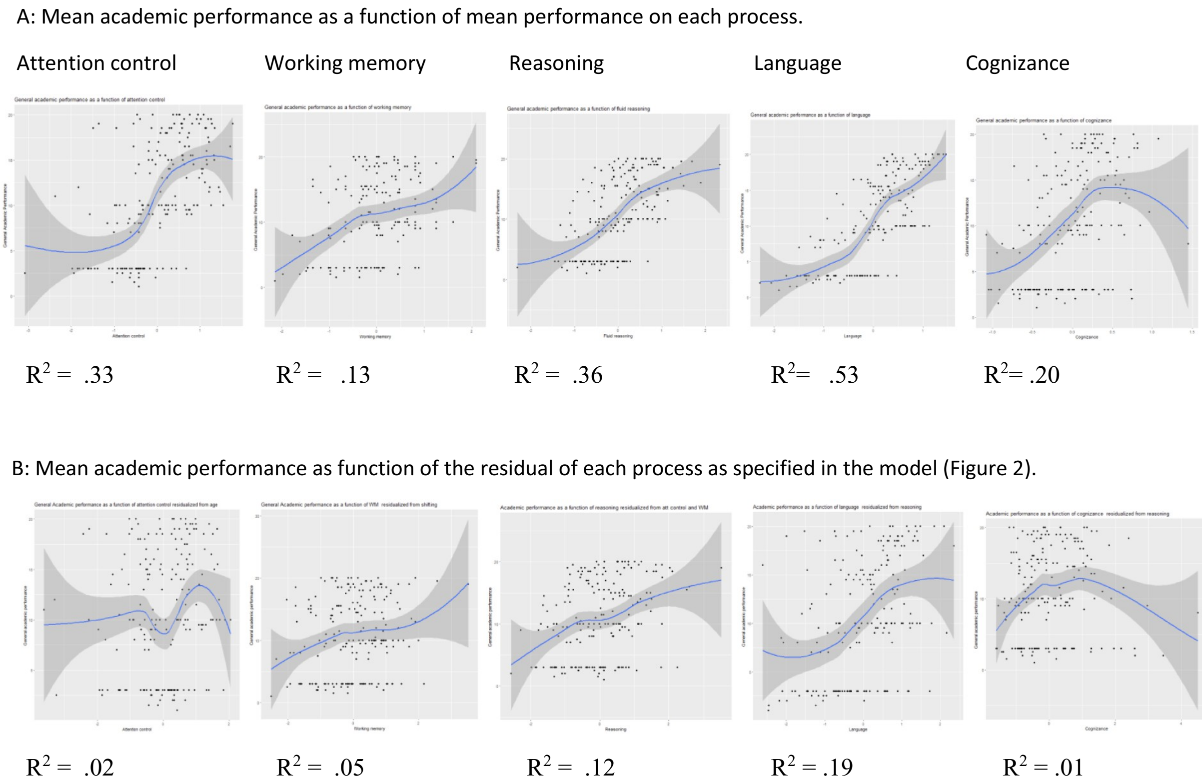

Fig. 4. Regressions of mean academic performance on mean performance on each mental processes and the residual of each process after partialling out the effect of other processes as specified in the model shown in Fig. 2. Note: attention residualized from age; working memory residualized from shifting; reasoning residualized from shifting and working memory; language and cognizance residualized from reasoning.

performance and mean standardized performance attained on each of the processes examined in the study (shifting is not shown because its relation with academic performance was very close to the relation between attention control and academic performance). Two aspects of these relations need special mention: on the one hand, there is a large variation between them, accounting from 13% (working memory) to 53% (language) of academic performance variance; on the other hand, the relation with cognitive ability (36%) was close to what is reported in the literature; interestingly, however, the relation with language was much higher. Panel B of Fig. 4 shows the relations of each process with academic performance after it was residualized according to the cascade model described above. Thus, it shows how each process relates individually with academic performance when it is purified from other processes. Notably, two of these relations practically vanished. On the one hand, the drastic effect of age on the relation between attention control (and shifting) and academic performance (2% of GAP variance) indicates that executive control carries developmental influences on school learning. On the other hand, the absorption of the cognizance-academic performance relation by cognition indicates that cognizance is fully commensurate with reasoning (1% of GAP variance). It may reflect cognitive changes and be predictive of academic performance, but its predictive power may be redundant to reasoning. However, working memory, reasoning, and language (5%, 12%, and 19% of GAP variance, respectively) do independently and individually contribute to school learning. Obviously, handling information in memory, inferential, and semantic integration as such are distinctly important for school performance, in addition to processing, representational, and integration efficiency represented by g.

4. General discussion

A school classroom is a very complex environment. It involves many children who differ from each other in their mental abilities, their personalities, their interests, and their family backgrounds. The teachers who teach and evaluate them also differ in education, abilities, personalities, social skills, and teaching styles and proficiency. Domains of learning, such as mathematics, science, and language, differ in knowledge and conceptual characteristics, posing different demands on learning; as a result, they pair differently with students' and teachers' profiles. Given the hugeness of individual and epistemic variability in classrooms, it is admirable that academic performance, independently evaluated by teachers, would be so highly predictable from the mental processes tested here. As predicted, 50% of variance of GAP was accounted for by our measures (common model in Fig. 2); g (29%) and language ability (32%) accounted for the lion's share of school performance variance. Notably, the amount of variance accounted for at the two levels of education was practically identical (63%).

Both findings above agree with the literature (e.g., Gustafsson & Balke, 1993; Roth et al., 2015). However, the pattern of these relations varied extensively with level of education, in line with the third prediction assuming developmental relativity in the power of cognitive predictors of academic outcomes. This is a unique finding suggesting that predicting school performance is not just a matter of individual differences. It is also a developmental issue because the very nature of g changes with development (Demetriou, Makris, Kazi, Spanoudis, Shayer, & Kazali, 2018; Demetriou & Spanoudis, 2018; Makris et al., 2017). It is reminded that reasoning predicted only 4% of variance in primary school as contrasted to 18% at secondary school. Also, there was a big difference between primary and secondary school in the mental processes complementing reasoning. It was cognitive flexibility (6%) and working memory (46%) in primary school and language (35%) in secondary school. Obviously, learning at primary school is highly dependent on cognitive processes allowing to focus on learning tasks and flexibly explore then, represent the information needed (working memory), in order to work out connections and mentally build concepts (reasoning) carrying forward the knowledge and relations presented by teachers. In fact, there is research showing that executive control is critical for the transition from preschool to primary school for the successful engagement behaviors needed in the classroom. These behaviors include attending to teacher's instructions, holding information in mind, inhibiting distracting responses, and flexibly adjusting to different instructions for different tasks (Nelson, Nelson, Clark, Kidwell, & Espy, 2017). Children weak in these tasks would lack the cohesion needed to build the concepts and skills required at the beginning of primary school. Executive functions are critical, for instance, for the integration of reading and writing at the beginning of primary school (Altemeier, Jones, Abbott, & Berninger, 2006).

In secondary school, these executive abilities are already established and taken for granted. Based on them, adolescents gradually construct the ability to grasp semantic and syntactic principles (language ability) underlying concepts in different domains of knowledge and science and integrate across them (reasoning). Also, learning in secondary school, by design, introduces students in the abstract and formal style of science in describing and explaining the world (Anderson & Krathwohl, 2000). Naturally, then, individual differences in dealing with language and reasoning in secondary school dominated as predictors of academic performance.

Attention is drawn to the differences in the hidden role of cognizance between primary and secondary school. In primary school cognizance was associated with experiences that may lead to it, such as flexibility, but not in secondary school. This reflects the fact that cognizance in each developmental cycle emerges out of the cognitive processes that are formed in each cycle and the experiences that they engender. In primary school mastering executive control and representational processes are the dominant developmental tasks. When these experiences become automated, this connection is lost. In adolescence, the dominant developmental task is reasoning and mental awareness (Demetriou, Makris, Kazi, Spanoudis, & Shayer, 2018). The effort to master reasoning generates reasoning-related awareness that it does reflect academic outcomes. However, this may be masked by the reasoning functions with which it covaries. In a sense, this may be psychology's dark matter. We may see its influences on other more obvious factors, but it operates in concealment, interacting with other mental processes. However, other studies showed that more broad aspects of cognizance, such as cognitive and academic self-concept (Demetriou, Kazi, Spanoudis, & Makris, 2019a, 2019b; Guay et al., 2003; Johannesson, 2017) and self-efficacy (Multon, Brown, & Lent, 1991) become increasingly powerful predictors of academic performance.

SES was clearly a factor involved at various levels. In line with prediction 4ii, it was found to influence academic performance directly, on top of cognitive influences. In fact, we found that this influence was considerably higher (21% of variance) than is reported in the literature (5–10% of variance) (Bradley & Corwyn, 2012; Sirin, 2005). Therefore, SES appears to negatively affect cognitive development as such but also performance at school. Obviously, this additional effect reflects the operation of processes other than cognition, such as interests, motivation, life-orientations, and work habits which differentiate children from different SES environments and are related to school learning (Sirin, 2005).

4.1. Educational implications

The findings presented here have several practical implications for education. In concern to evaluation, it is appropriate for diagnostic tools addressed to different levels of education to emphasize different processes. Specifically, tools addressed to primary school must include executive and working memory processes, together with reasoning. In secondary school emphasis would have to shift to semantic and linguistic processes, together with reasoning. Awareness and self-evaluation process must also be addressed to allow differentiations between students that may need special support in putting their cognitive abilities to application in learning tasks. This study suggests that the need for updating our diagnostic tools would benefit precision of cognitive diagnosis as a tool for that may guide educational evaluation and individually and developmentally targeted interventions.

The developmental relativization of emphasis would also be reflected in programs aiming to provide support for various processes. This support would need to focus on what is developmentally relevant and important. In early primary school, programs must refine executive processes and motivation control to efficiently engage students in learning for as long as needed to master new skills or concepts. In late primary school reasoning and information management, together with building self-organization strategies must acquire priority. The very processes in developmental g must become the object of learning vis-à-vis specific and grade appropriate tasks in different school subjects: e.g., mastering syntax and semantics in language; implementing reasoning in different domains, such as analogies, fractions, decimals, or early algebra in mathematics or organizing information to derive valid conclusions in the sciences. In secondary school, education should focus on sharpening self-understanding and self-management in implementing different cognitive processes. That is, it must lead adolescents to construct accurate self-representations for their cognitive profile so that they embark on appropriate choices and acquire problem-solving strategies and interests tuned to their profile so that they maximize the output of their activity.

4.2. Conclusions and limitations

In short, this study showed the following: (1) Cognitive and language ability strongly predict academic performance. (2) Different cognitive factors dominate as predictors in primary and secondary school; cognitive flexibility, working memory and reasoning dominate in primary school; language and reasoning dominate in secondary school. (3) Cognitive self-evaluation predicts academic performance only in secondary school, but this is masked by reasoning. (4) SES influences academic performance independently of its possible influence on cognitive ability.

No study is free of limitations. One limitation of this study is the lack of measures addressed to personality, motivation, and self-representation measures. These measures would help dissociate motivational and dispositional influences on academic performance from the cognitive measures used here. There is research showing that self-efficacy beliefs (Zimmerman, 2000), openness and conscientiousness (Demetriou, Spanoudis, Žebec, Andreou, Golino, & Kazi, 2018; Demetriou et al., 2019a; Poropat, 2009), and cognitive self-concept (Demetriou et al., 2019a, 2019b, submitted) relate with academic performance on top of cognitive ability. Also, in cross-sectional studies such as this one, relations may be confounded by unknown factors. Longitudinal research is needed to map age changes in the relative contribution of each of these processes and capture their causal interactions at different levels of schooling. Even then, causal relations can only be specified when the variables of interest are experimentally manipulated. This type of research is obviously very difficult to conduct.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.intell.2019.101404.

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