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Mapping the evolving core of intelligence: Changing relations between executive control, reasoning, language, and awareness

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ABSTRACT

We explored relations between attention control, shifting flexibility, working memory, reasoning in different domains, awareness about reasoning, and language from 9 to 15 years of age. For this aim 198 9-, 11-, 13-, and 15-years old participants were examined with tasks addressed to all processes. All processes developed systematically throughout the period studied. Structural equation modeling revealed a powerful common construct underlying reasoning and language processes. All domain-specific cognitive, language, or awareness processes represented this common factor equally well. This factor was related to attention control, shifting flexibility, and working memory but this relation varied with development, being dominated by attention control at 9–11, inferential-representational processes at 11–13, and awareness-symbolic processes at 13–15. Piecewise linear modeling showed that transition points between phases are marked by phase-dominating processes. Modeling ability and age differentiation with increasing g suggested some ability differentiation at the end of developmental cycles suggesting that g-ability relations are re-worked anew in successive developmental cycles. Implications for developmental, cognitive, and brain science are discussed.

1. Introduction

Is there a core in intelligence that is present in all major mental functions, such as attention, executive control, working memory, reasoning, and awareness? What does it involve? Does it change with development? Answers to these questions do exist in psychometric (Carroll, 1993; Deary et al., 1996; Jensen, 1998), developmental (Carey, 2009; Case, 1992; Halford, Wilson, & Phillips, 1998; Piaget, 1970; Tenenbaum, Kemp, Griffiths, & Goodman, 2011), and cognitive science (Carruthers, 2002; Fodor, 1975). However, they are not commonly accepted. Obviously, valid answers would be important both for our understanding of the human mind and its implications for clinical and educational practice. This is what motivated this study. In this introduction, we first review literature about a common mental core. Then, we review research on the relations between the processes involved. Finally, we summarize a model integrating these literatures into an overarching framework about mental architecture and development and state predictions to be tested by this study.

1.1. General intelligence, language of thought, awareness and language

Classical theories of the human mind assume that there is a common mental core underlying thought and understanding. In Spearman's (1904) theory, general intelligence (or G) is defined as the education of (i) relations between objects or events and (ii) their correlates, i.e., relations between relations (Carroll, 1993; Jensen, 1998). In current psychometric theory these processes are associated with fluid intelligence (Gf), which is differentiated from crystallized intelligence (i.e., Gc, knowledge and skills emerging from the functioning of Gf) (Cattell, 1963; Gustafsson & Undheim, 1996).

Grasp of relations is equally important in developmental theory (Piaget, 1970). However, the emphasis is on the organization of underlying mental operations into reversible structures allowing understanding of stability and change in the world and grasping the (physical or logical) implications of alternative physical or mental actions. For instance, the various aspects of reality, such as matter, quantity, number, length, area, etc., may remain stable despite changes in the relations between some of their dimensions. The conception of this core in current developmental theory remains impressively similar to its classic versions: It is still based on the "blessing of abstraction" (Tenenbaum et al., 2011), which is initially guided by statistical regularities in the environment and then by rules underlying relations between these regularities.

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Cognitive science focused on the Language of Thought (LOT), searching for the fundamental mental elements involved in this core and the rules underlying their relations (Schneider & Katz, 2011). In its classic version (Fodor, 1975), the basic units of LOT are atomic symbols that stand for representations bearing meaning for the thinker (e.g., “cat”, “dog” “animal”, “life” may all be valid symbols). These symbols may be combined by a combinatorial syntax that yields infinitely compounded representations, whose meaning is defined by the symbols involved and the rules of syntax used (e.g., “If Max is a dog, he barks”). Preservation of truth is a basic property of LOT in that the transformation of true premises (symbols) always results into further true premises: Any set of combined representations can be translated into any other set once initial truths are carried across sets. For many, the rules of this syntax are the rules of logical reasoning, whatever they are (Johnson-Laird & Khemlani, 2014; Rips, 1994).

Where do the rules of thought come from? In cognitive and developmental science answers vary from the extreme Whorfian (Whorf, 1956) hypothesis of complete determination of thought by language to complete independence assuming that language is a conduit for the communication of thoughts without any other important effect on it (Hurlburt, 1993). In developmental psychology, Vygotsky's and Piaget's theories may be taken as exemplars of the polarity about the origins of the rules of thought. At the one extreme, Vygotsky (1986) claimed that social scaffolding and language shape thought. Specifically, inner speech (silent language addressed to oneself) expresses and controls thought and operates as the medium for the interiorization of the formative influences of culture. At the other extreme, Piaget (1970) claimed that the rules of thought emerge gradually from the coordination of mental operations. This coordination becomes increasingly abstract obeying logical rules able to express the relations that can be handled at different developmental phases. Language and other representational functions, such as perception and imagery, are subservient to this coordination. Therefore, the state and complexity of language reflects the state and complexity of the current mental structure. Interestingly, the psychometric answer is very similar to the Piagetian answer: Language, as the main symbolic vehicle of Gc, expresses rather than shapes Gf (Carroll, 1993).

Recently, Carruthers (2002, 2009) took an intermediate position. He postulated that “language is the vehicle of non-modular, non-domain-specific, conceptual thinking which integrates the results of modular thinking.” (Carruthers, 2002, p. 666). Specifically, the capacity of thought to integrate “different content-bearing items into a single thought” (p. 668) is patterned on the fundamental properties of syntax: That is, recursivity, compositionality, generativity, and hierarchical organization.

How much awareness does the mental core involve? In psychometric theory, awareness is not accepted as part of intelligence (Jensen, 1998, 2000). In developmental theory awareness is present but its relations with the other constructs are weakly specified. In Piaget's theory, reflective abstraction is a major factor of cognitive development. It operates on representations, abstracting their underlying relations and projecting them to a higher level of functioning, thereby opening transition to a next stage of development (Piaget, 2001). However, Piaget assumed that reflective abstraction does not involve awareness until the advent of formal operations. Metacognition (i.e., knowing about knowing) is a relevant construct loosely associated to Piaget's reflective abstraction (Efklides, 2008; Flavell, 1979). Recent developmental research showed that awareness of mental processes develops systematically from infancy through adulthood, contributing to cognitive development (Flavell, Green, & Flavell, 1995; Pillow, 2012; Spanoudis, Demetriou, Kazi, Giorgala, & Zenonos, 2015 and social interactions (Wellman, 2014).

In cognitive science, metacognition is associated to mindreading and it is ascribed a causal role in the functioning of reasoning, such as selection and evaluation of propositions in an argument (Carruthers, 2009). In this function, awareness is related to language because language is the vehicle for “externally representing propositional thought” (Chater, 2002, p. 680), rendering it available to monitoring and awareness (Carruthers, 2009). Also, language makes executive control possible because it allows individuals to address self-regulatory instructions to themselves (Perner, 1998).

1.2. Decomposing the mental core into its elementary components

Research in all traditions sought to decompose the mental core into more fundamental components. Various aspects of attention control, executive control, and working memory were considered as its building blocks. Several theories ascribed individual differences (e.g., Jensen, 1998, 2006; Kyllonen & Christal, 1990) and intellectual development (Kail, 2007; Case, 1985; Diamond, 2013; Pascual-Leone, 1970; Zelazo, Craik, & Booth, 2004) to one or more of these constructs. A hierarchical cascade was proposed as the model of the relations between these processes. This model postulated that each process is embedded into the next more complex process in the hierarchy (Fry & Hale, 1996; Kail, 2007; Kail & Ferrer, 2007; Kail, Lervag, & Hulme, 2015). Fig. 1 outlines this cascade.

Specifically, attention control lies at the bottom of the hierarchy because it is very basic, keeping mental focus on target against salient but irrelevant object characteristics (Diamond, 2013; Rothbart & Posner, 2015). Flexibility in shifting across stimuli or responses according to complementary goals is the next level in the hierarchy because it brings mental focus under the executive control of the thinker, allowing deployment of mental or behavioral plans (Deak & Wiseheart, 2015). Working memory resides higher because it involves, in addition to an executive program, information to be stored and related storage and recall processes (Baddeley, 2012; Cowan et al., 2007; Kane, Bleckley, Conway, & Engle, 2001). Reasoning and problem solving in different domains resides higher because it involves, additionally, inferential processes inter-relating representations in sake of valid conclusions (Johnson-Laird & Khemlani, 2014; Rips, 1994; Markovits, Thomson, & Brisson, 2015).

1.3. An integrated developmental-differential model of the mind

The cascade model is developmentally weak because it does not differentiate between developmental phases, assuming that the hierarchy above would be similarly valid throughout development. However, the relations between processes might vary as a function of developmental phase, reflecting differences between processes in developmental pacing. Recently, Demetriou and colleagues (Demetriou, Spanoudis, & Shayer, 2014) proposed a model specifying the role and relations of the various processes in each successive developmental phase.

Specifically, they suggested that a common core of processes is always present. It involves three fundamental processes: Abstraction, alignment, and cognizance (AACog). Abstraction enables pattern identification on the basis of perceptual similarities or statistical regularities in the input. Alignment is a relational mechanism mapping representations onto each other in search of relational similarity. Cognizance is awareness of the objects of cognition, cognitive processes, and cognitive goals. Cognizance is important because it protracts experience from past to present, rendering it available to abstraction and alignment. It draws on two mechanisms: (i) Reflection (mental re-enactment of past experiences so that they are available to abstraction and relational elaboration); and (ii) metarepresentation (encoding of abstraction and relations into new representations for future use). Executive control is a special expression of cognizance in that it reflects the self-regulation possibilities allowed by cognizance. Another expression is self-evaluation which reflects awareness of relations between mental goals, intervening processes, and outcomes. Conceptual development is self-propelled because AACog continuously generates new mental content expressed in representations of increasing inclusiveness and resolution (Demetriou, Spanoudis, & Shayer, 2014). This core is minimally

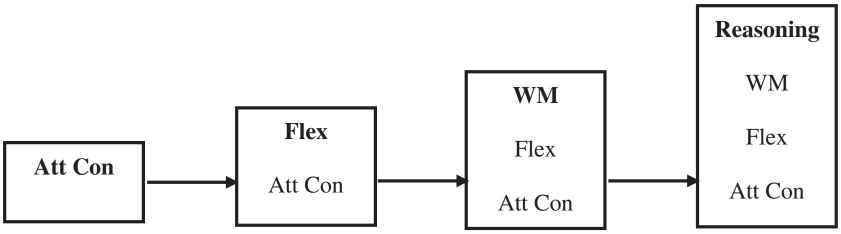


Fig. 1. A general representation of the cascade model showing that each next level includes processes specific to this level together with all lower level processes. Note: The symbols Att Con, Flex, and WM stand for attention control, flexibility of shifting, and working memory, respectively.

inferential in that it is not associated with specific reasoning processes, such as inductive or deductive reasoning. Therefore, it is more general than psychometric G or the structures discussed in developmental theories.

AACog evolves through four developmental cycles, with two phases in each. Transitions across cycles are associated with the emergence of new forms of representation; transitions within cycles are associated with increasing awareness of the new representations and ensuing increasing skill in using them. In succession, the four cycles operate with episodic representations (birth to 2 years), realistic mental representations (2–6 years), generic rules organizing representations into conceptual systems (6–11 years), and overarching principles integrating rules into epistemic systems where truth and validity can be evaluated (11–18 years). Transitions within cycles occur at 4 years, 8 years, and 14 years, when representations start to become explicitly cognized so that their relations may be worked out and metarepresented into the representations of the next cycle (Demetriou et al., 2014). Cognizance recycles over these cycles, because awareness of representations in each cycle builds up with their attainment (Demetriou et al., 2014).

In this paper we focus on the two cycles attained after the age of 6 years as this study is concerned only with them. In early childhood, toddlers show an awareness of perception as a source of knowledge but it is only at 4–5 years that they are aware of their own and other persons' representations (Flavell et al., 1995; Pillow, 2012). At the beginning of the next cycle children are aware of mental functions such as thought or memory but they do not clearly differentiate between them nor do they associate each with specific processes. This differentiation appears at 8–9 years, when children show awareness of underlying mental processes connecting representations, such as syntax in language (Olson & Astington, 2013) or inference in reasoning (Moshman, 2004). At the beginning of the third cycle children are not aware of the constraints underlying possible relations between rules. This awareness appears after the age of 13–14 years, allowing adolescents to explicitly evaluate truth and validity and recognize logical fallacies (Demetriou et al., 2014; Christoforides, Spanoudis, & Demetriou, 2016).

Each cycle culminates in a particular executive control program that is the vector of the cycle's representational and cognizance possibilities. In the rule-based cycle, the executive program allows coordination of mental spaces and fluency in shifting between them, as in divided attention tasks, or tasks requiring systematic navigation through different conceptual categories (e.g., say all fruits coming to your mind, then all animals, then all furniture). In the principle-based cycle, this program is extended into an *inferential relevance mastery program* enabling the adolescent to evaluate inferences for relevance and consistency according to the specificities of the problem at hand and criteria for relative truth and validity (Demetriou et al., 2014).

Thought in different domains expresses the executive possibilities of each cycle. For instance, in the first phase of rule-based thought, the integration of various conceptual spaces related to number, such as object arrays, number words, and counting, into a common mental number line exemplifies a rule in the domain of quantitative reasoning. In the second phase the rule-based executive is flexible enough to allow alignment and bridging of several rules, such as the mental number line above and measurement, allowing construction of complex conceptual spaces, such as length, and related skills. In the same fashion, children at this phase perform well on two-way Raven's matrices; they execute mental rotations requiring to mentally visualize how components of an image are transformed relative to each other; they can conceive alternative variations of combinations between several factors and identify the causal relation between a causal factor; they are capable of modus ponens and modus tollens inferences requiring the combination of a series of propositions as reflected in actual experience.

Early in the next cycle, at 11–13 years, adolescents grasp relations between rules, encode them as such, and reduce them to general principles. However, in this phase, the executive is not yet directed by a precise evaluative metasystem specifying when performance is successful, when solutions are consistent with a general truth-value system, etc. Thus, they may solve complex Raven matrices requiring grasping a principle underlying several transformations, but they may still be deceived by logical illusions (Zebec, Demetriou, & Topic, 2015). This is established in the next phase, allowing adolescents to check conditional reasoning arguments for truth, specify analogical relations within and across levels of different hierarchies, systematically isolate variables to test alternative hypotheses, and visualize transformations of complex images along multiple dimensions. Thus, adolescents may solve complex problems requiring a rich knowledge base and refined plans because they are guided by principles they are explicitly aware of (Demetriou et al., 2014).

Thus, representational and inferential processes in the common core are reformed in each cycle. As a result, this core is differentially related to indexes of mental efficiency at the initial and the last phase of each cycle. Specifically, thought changes at the first phase of each cycle (i.e., at 6–8 and 11–13 years) are predicted by processing efficiency measures, such as attention control, reflecting increasing mastery of the new executive core. At the second phase (i.e., 4–6, 8–10, and 13–16 years) thought changes are predicted by working memory, reflecting the elaboration of relations between representations which depends on working memory (Demetriou et al., 2013, 2014). However, cognizance rather than efficiency is the crucial factor of transition to the next cycle (Christoforides et al., 2016; Spanoudis et al., 2015), because reflection becomes increasingly sharper and more focused rendering metarepresentation more efficient.

This state of affairs relates to a long debate about the relations between the common core and specific processes at different levels of this core. Spearman (1927) suggested that abilities differentiate from each other with increasing g because higher ability allows more flexible learning in different domains causing abilities to depart from each other. The developmental adaptation of Spearman's differentiation hypothesis assumes that abilities differentiate with growth because of development in g. Although earlier research provided some support to this hypothesis (Deary et al., 1996; Detterman & Daniels, 1989), recent research employing stricter modeling methods provided rather weak and inconsistent evidence in favor of ability differentiation and no evidence for age differentiation (Molenaar, Dolan, Wicherts, & van der Maas, 2010; Tucker-Drob, 2009). The present model offers a reason for this state of affairs. Specifically, this model suggests that ability differentiation may be possible at the end of developmental cycles but no age differentiation is to be expected. Specifically, at the end of developmental cycles learning possibilities increase because of the command of the new representational and inferential abilities. This may increase variability across individuals. However, no age differentiation is to be expected because relations with the common core are constructed a new in each cycle. In fact, an increase in the strength of relations between abilities and g (i.e., de-differentiation) may be expected in the first phase of each cycle to reflect the emergence of the new form of the common core and the re-elaboration of its activation in different domains.

1.4. Predictions

Based on the literature reviewed above, the following predictions were tested. First, all processes would improve with age to reflect changes in their underlying common core. However, specific developmental patterns are expected. (i) On the one hand, success on reasoning tasks should scale according to their phase affiliation. (ii) On the other hand, variations in the relations between processes with age would signify transition points reflecting the specific cognitive profile of each phase.

Second, in concern to structure, (i) a strong common factor (G) underlying all processes would stand for the common core. Theories dispute the identity of this core: Each of the processes discussed here was considered to be a privileged representative of this core by some theories (e.g., speeded performance requiring attention by psychometric theories, executive control and working memory by current cognitive and cognitive developmental theory, and inferential processes by classical psychometric and developmental theory). This state of affairs yields two alternative predictions: (ii) Processes dominating in the core would relate to G more closely than the rest. Alternatively, (iii) if this core *is equally present in all processes*, as assumed by the AACog model, each process-specific factor would stand equally well for factor.

Third, the relations between processes would vary with age to indicate changes in their relative contribution to the functioning of the core. Specifically, (i) with increasing age, the relations between processes lying higher (e.g., reasoning and cognizance) in the hierarchy would strengthen to reflect a shift in the dependence of the common core from simpler to more complex processes. (ii) Thus, some differentiation of ability would be expected in concern to abilities well integrated in the core, such as processing efficiency and working memory. However, no age differentiation is to be expected because g-ability relations are reworked in each cycle.

2. Method

2.1. Participants

A total of 198 participants were examined, about equally drawn among 3rd (N = 55, 25 male; mean age = 8.56, SD = 0.35, range 7.92–9.50), 5th (N = 44, 26 male; mean age = 10.71, SD = 0.59, range 9.33–12.08) (primary school), 7th (N = 53, 26 male; mean age = 12.65, SD = 0.43, range 12.08–14.75), and 9th grade (N = 46, 25 male; mean age = 14.61, SD = 0.33, range 14.17–16.00) (secondary school). Henceforth, the four groups will be called 9-, 11-, 13-, and 15-year olds, respectively. These participants lived in Alexandroupolis and Veria, two cities in northern Greece. They were all Greek and native speakers of Greek and they were generally representative of the general population, although there was a tendency for middle class families to have a higher representation in the present sample: Specifically, 42% (25%), 32% (42%), and 26% (30%) of their parents had university, secondary, and compulsory education (i.e., 16, 12, and 9 years, respectively (numbers in parentheses show the distribution of each level of education in the country, according to the 2011 census).

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). The words κόκκινο (red), πράσινο (green), and κίτρινο (yellow) were used because they have the same number of letters.

In the number domain, several "large" number digits (e.g., 4, 7, and 9), which were composed of "small" digits (i.e., the same digits as above), were prepared. 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). For speed, participants recognized the large congruent numbers. For attention control, participants recognized the component number of incongruent numbers.

In the visual domain, several geometrical figures were composed as specified above in concern to the number digits. That is, large 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.

The reliability of this battery was high (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.

Three scores were computed, one for each task. These scores reflected the higher level attained on each task, credited if at least one of the sets addressed to this level was successfully performed. Although rather low, the reliability of these tasks (Cronbach's alpha was 0.49) was in the range expected for tasks addressing different aspects of working memory (Conway et al., 2005). Fortunately, using these scores in latent variable models largely compensates for this weakness (Bentler, 2006).

2.2.3. Cognitive flexibility

To examine cognitive flexibility, a series of Stroop-like tasks similar to those addressed to speed and attention control was used. These tasks were also 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 presented stimuli. Forty stimuli had to be recognized on the basis of a main rule (e.g., the color, the large number figure, the large geometrical figure for the verbal, the numerical and the figural cognitive flexibility task, respectively); the remaining 10 had to be 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.

2.2.3.1. Visually cued color-shape task–VCCST. This task was first 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). Their task was to sort several test items presented at the center of the screen beneath the target row, either by color or shape. Below each test item there was a symbol (X or Y) indicating how the item must be sorted (X for color and Y for shape). Four keys on the keyboard corresponded to the items in the central row. Two sets of the test were created. There were 50 items in each set; 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 one 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. According to Zelazo et al. (2004), perseverative responses would be correct under the other rule; all other errors are non-perseverative.

The reliability of these tasks was good (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 & Kyriakides, 2006) and used in several studies (e.g., Demetriou & Kazi, 2001, 2006; Demetriou, Mouyi, & Spanoudis, 2008). For the present purposes we selected tasks addressing rule-based and principle-based reasoning.

2.2.5. Inductive and deductive reasoning

2.2.5.1. Verbal analogies. Children solved four verbal analogies. The first two were of the a:b::c:d type: The first involved familiar terms and relations where the a, b, and c components were specified and the participant had to choose the d component among three alternatives (ink: pen::paint:: - [color, *brush*, paper]). The second involved familiar terms but the participant had to fully construct the c:d pair (bed:sleep:: - [paper, *table*, water]: - [*eating*, rain, book]). The third required grasping third-order relations (i.e., a:b::c:::d: e::f) (children:parents::family):::(students:teachers:: - [school, *education*, lesson]). Finally, the fourth involved relations fourth-order ({(tail:fish::feed:mammals)::: - [*movement*, animals, vertebrates]}::::{(propeller:ship::wheels:car)::: - [vehicles, *transportation*, carriers]}). The participant had to choose the correct concept (shown here *in italics*) among the three alternatives provided for each missing element. The four analogies address the four phases spanning the two target cycles, respectively.

2.2.5.2. Verbal reasoning. Four reasoning tasks were used: An easy transitivity task solved at the first (i.e., if $p > q$ and $p > r$, what is correct, $q > s$, $p > s$, or none) and a modus tollens task (i.e., if p then q, not q, therefore not p), solved at the second phase of rule-based reasoning; a difficult transitivity task (i.e., if $p > q$ and $r < s$, what is correct, $r > p$, $r < r < p$, or none) solved at the first and the fallacy of affirming the consequent (if p then q, q, what is correct, not p, p, or none), solved at the second phase of principle-based reasoning.

2.2.6. Quantitative reasoning

Three aspects of the quantitative reasoning were assessed: The ability to mentally execute the four arithmetic operations in combination to each other, quantitative analogical reasoning, and algebraic reasoning. They were as follows:

2.2.6.1. Numerical operations. There were four problems addressed to the ability to decipher arithmetic operations. The participants were asked to specify the numerical operation symbolized by each symbol in the equations following: $(9 * 3) = 6$; $[(2 \$ 4) \# 2 = 6]$; $[(3 \$ 2 * 4) \wedge 3 = 7]$; $[(3 \$ 3) \# 1 = (12 \$ 3) * 2]$. The first two are solved in the first and the second phase of rule-based reasoning and the last two are solved in the first and the second phase of principle-based concepts, respectively.

2.2.6.2. Numerical analogies. There were seven mathematical analogies. The six were as follows: 6:12::8:?; 3:9::6:?; 6:8::9:?; 6:3::8:?; 3:1::6:?; 6:4::9:?. Difficulty was manipulated with reference to the type of mathematical relationship involved: In the first three items numbers increased and in the other three the numbers decreased. Numbers in each set changed by a factor of 2, 3, or 1/3. The last item required third order proportional reasoning: Participants had to specify which of the six items above involved the same relation with (24:16::12:8).

Analogies involving increase or decrease by a factor of 2 or 3 require second-phase rule-based reasoning, because they require to abstract relations between clearly defined number lines. Analogies involving change by a fraction are solved at the first phase of principle-based reasoning, because they require explicit grasp of the principles underlying analogical relations between numbers and the ensuing application of the necessary operations to transform the particular analogies along these principles. The last addressed second phase principle-based reasoning because it required abstracting the formal relations between analogies.

2.2.7. Causal reasoning

Two aspects of the causal reasoning were assessed: Combinatorial thinking and hypothesis testing by experimentation.

2.2.7.1. Combinatorial thinking. Participants were asked to specify all possible combinations of drawing the following sets of balls out of a box: two red and a green ball; a blue, a red and green ball; two red and two blue balls; two red, a green, and a blue ball. The first two may be solved by phase one and phase two rule-based reasoning and the last two by phase one and phase two principle based reasoning.

2.2.7.2. Hypothesis testing. Hypothesis testing was addressed by the *tracks task*. There were two identical tracks, four weights (i.e., two big and two small weights), and four engines (i.e., two big and two small ones) depicted in a picture. The participant had to choose the right combination of weights and engines to test how weight affects the speed of the tracks. This task examined the understanding that to test the possible effect of a factor all factors must be held constant but the one tested.

There were three items: In the first, the manipulations were given and participants must specify the factor tested; in the second item, participants must hold one and in the third must hold two factors constant. The first item addressed rule-based causal reasoning because it requires aligning an effect with a cause. The second addressed the first phase of principle-based reasoning because it requires grasping the “isolation of variables” principle. The third addressed the second phase of principle-based thought, because it requires applying this principle on two interacting variables.

2.2.8. Spatial reasoning

The spatial thought battery included 5 tasks addressed to image manipulation, mental rotation, and coordination of perspectives. They were as follows:

2.2.8.1. Mental rotation. Two tasks assessed mental rotation. In the *clock task* each item depicted a clock with one hand always pointing to the 12:00 position and the other pointing to 12:15, 12:30, or 12:45. There was a geometrical figure (e.g., a triangle) drawn on the hand pointing to 12:00 o'clock and the participant had to imagine how this figure would look like when this hand would rotate to come on top of the other hand. Difficulty varied with the complexity of the figures involved and the degree of rotation of these figure (e.g., a diamond with tilted parallel lines as inside background rotated by 45°, a triangle with a tilted line rotated by 90°, a semicircle rotated by 270°, a large square including a smaller square at the upper right quarter, rotated by 270°). In the *letters* task the participants were asked to specify the three-dimensional object to come by rotating each of three letters (H, Ψ, and P) around their vertical axis.

The *clock* task addressed rule-based reasoning. The items involving one dimension may be solved at the first and the items involving two dimensions may be solved at the second phase of rule-based reasoning. The *letters* task require principle-based reasoning because they are more abstract: 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.

The reliability of cognitive tasks was high (Cronbach's alpha was 0.83).

Two types of scores were computed. Two sum scores for each domain, one for each subdomain described above to allow determination of domain-specific factors and four sum scores, one for each of the four domains.

2.2.9. Self-evaluation

Two types of subjective evaluations were obtained to explore the ability to evaluate one's own problem solving. Specifically, after solving each of the cognitive tasks above, participants were asked to evaluate the success of their performance and the difficulty of the task in reference to a five-point scale. For success evaluation, the question was: "How right do you think your solution on this task was?" For difficulty evaluation, the question was: "How difficult this task was for you?" A 5-point scale was used in both cases: (1) Not (successful, difficult) at all … (5) very (successful, difficult). Success evaluations are taken to represent the evaluative aspect of cognizance that enables thinkers to monitor their performance vis-à-vis cognitive goals and probably regulate problem solving attempts. Difficulty evaluations are taken to represent the ability to monitor task complexity and/or cognitive load and probably regulate problem solving relative to its mental cost.

The reliability of success (0.93) and difficulty evaluations (0.91) was very high.

To relate these scores with actual performance and render them reflect self-evaluation accuracy, domain-specific and phase-specific self-evaluation accuracy indexes were created. For domain-specific indexes, the following transformations were applied. First, difficulty evaluations were inverted to vary in the same direction with success evaluations. Second, each domain performance sum score and each domain success and each difficulty evaluation sum score was transformed into a z score. Third, each success evaluation z score and each inverted difficulty evaluation z score was subtracted from its corresponding actual performance z score. Finally, the two domain-specific evaluation scores were averaged to yield the self-evaluation accuracy index for each of the four domains. It is noted that this approach to estimating self-evaluation accuracy was adopted by several researchers (Demetriou & Kazi, 2001, 2006; Leonardelli, Hermann, Lynch, & Arkin, 2003).

For phase-specific indexes, the following transformations were applied. First, a set of three performance sum scores were created for rule-based tasks and another set for principle-based tasks. Each score in each of these two sets involved tasks from all four domains. Second, in the same fashion, the corresponding success and the corresponding difficulty phase-specific evaluation scores were created. Finally, each of these evaluation scores was first subtracted from its corresponding success evaluation score and then each pair was averaged in the fashion above, yielding three evaluation accuracy indexes for rule-based solutions and three evaluation indexes for principle-based solutions.

2.2.9.1.1. Language. To test language ability, several tasks addressed vocabulary, syntax, and semantics both orally and in writing. To address vocabulary orally, the following tasks were used: (i) children had to specify 13 words whose first phoneme and definition was given (e.g., fr … means a person whom we love); (ii) give the definition of 13 words (e.g., "What is a bed?"); iii) the Greek version of WISC-III vocabulary was also given. To address syntax, children heard 15 sentences and they had to find the grammatical/syntactical mistakes in sentences (e.g., "Three friends takes the spoon"). To address semantics, children had to combine simple sentences into more complex sentences that would be coherent in meaning (e.g., "I am old" and "I am tall" into "I am old and tall").

Two written tasks addressed syntax. (i) Children were given 7 sets of scrambled words (each involving from 7 to 11 words) which they should put into syntactically acceptable sentences (e.g., child, tree, climbs, the, onto). (ii) Children were given 7 stories describing actions in the present tense and they had to change all verbs into the past tense. To address semantics, two tasks were used. The first involved eight sets of 5 scrambled sentences; their task was to arrange the sentences in each set into a meaningful story. The second task addressed involved seven stories. Children first read each of the stories and they then answered 4 questions probing their understanding of it (i.e., find a title, recall information, draw a conclusion, find a sentence that does not fit to the story).

This test was standardized in Greece and is used as a measure of language ability (Tzouriadou, Syngollitou, Anagnostopoulou, & Vacola, 2008). 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 (i.e., (Cronbach's alpha was 0.79, 0.80, and 0.84, for vocabulary, syntax, and semantics, respectively).

Two sets of scores were computed for language tasks. Three mean scores, (i.e., vocabulary, oral, and written language) were used in models involving a single language factor. Three sum vocabulary scores, three sum syntax scores, and three sum semantics scores were used in models involving domain-specific factors for language.

2.3. Procedure

All participants were tested individually by the second author. Participants participated voluntarily upon consent by parents and schools. Testing took place at schools in a specifically provided room. Testing was organized in four 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. Each session lasted for approximately 45 min. The four sessions addressed to a participant took place on four consecutive days.

3. Results

To test our predictions, three types of analyses were applied. First, to map developmental pattering as a function of age, an ANOVA was applied on the mean z scores standing for performance on each process. Second, we used piecewise linear modeling to identify the onset, offset, and rate of change for developmental phases as they predicted by AACog theory. Third, to specify the organization of processes a series of structural equation models were tested. Two participants, a 9- and a 15-year old, were dropped as outliers from all analyses, because their contribution to normalized multivariate kurtosis was large (Bentler, 2006).

A post hoc power analysis was conducted using GPower (Faul, Erdfelder, Lang, & Buchner, 2007). The effect size set to 0.25 which is considered to be medium according to Cohen's (1988) criteria. With an alpha = 0.05 two-tailed, a sample size of 198 and 4 level in the between subjects factor (age), the study power (1-β) estimated to be 0.84. Therefore, our sample size is adequate in order group differences to reach statistical significance at the 0.05 level. Thus, it is unlikely that our findings can be attributed to a limited sample size.

3.1. Developmental patterns

Percentage attainment on the reasoning tasks came as expected. Fig. 2 shows that 9-year olds solved first level rule-based tasks (61%); however, their performance on all other levels was considerably lower (43%, 29%, and 10% success on the three higher levels, respectively). Eleven-year olds succeeded on both the first (80%) and the second level of rule-based tasks (67%); their performance on the first (47%) or the second level (16%) of principle-based tasks was much lower. The majority of 13- (69%) and 15-year olds (76%) solved first level principle-based tasks and all lower levels tasks (~70%). However, only a minority of 15-year olds solved the second level principle-based tasks (32%); performance of younger children on these tasks was even lower (10%, 16%, and 28% for 9-, 11-, and 13-year olds, respectively). This is consistent with findings suggesting that this level is attained by only a minority of adults (Demetriou & Kyriakides, 2006).

To map developmental trends across the various processes, the mean z scores of performance on the six processes were subjected to a mixed 4 (the four age groups) × 6 (attention control, shifting, working memory, reasoning, language, and cognizance) ANOVA (attention control and shifting z scores were inverted to vary in the same direction with the rest). Fig. 3 presents the main trends uncovered by this analysis and Supplementary Table 1 presents the raw means and standard deviations involved. In line with the first prediction, the effect of age was very powerful, $F(3, 192) = 65.45$, $p < 0.0001$, $\eta^2 = 0.51$, reflecting the systematic improvement of performance across all age groups and processes. Also, the age × process interaction, $F(5, 190) = 16.35$, $p < 0.0001$, $\eta^2 = 0.30$, was highly significant, suggesting that the pattern of age differences varied across phases and processes (following Bonferroni, acceptable $p < 0.01$).

Fig. 3 shows two notable trends. First, development in the 9 to 11 years phase was more concerted than in the 11–13 or the 13–15 years phase: Differences between processes were smaller in the first than in the other two phases. Differences widened in the 11–13 years phase with change in attention control and language exceeding all other processes and working memory halting. In the 13–15 years phase, scores converged again.

3.2. Delimitating developmental phases

This study focused on three successive developmental phases, namely later rule-based (8–11 years), early (11–13 years) and late principled-based thought (13–15 years). We hypothesized that transitions between phases would be marked by the onset of changes related to the processes primarily acquired at the phase concerned. Also, we anticipated an offset of changes at the end of phases marking the consolidation of abilities. These onset and offset time-points can be conceptualized as breakpoints that connect regression lines with different slopes (rates of change). These slopes describe the direction and rate of change in abilities before and after the onset/offset of change.

Segmented or piecewise linear regression complements the ANOVA above allowing to estimate a) the time-point at which a transition occurs and b) the direction and rate of developmental change before and after transition. We performed a series of linear and segmented regression analyses to identify the time-points where developmental changes may happen. We used the "segmented" R package (Muggeo, 2008) that is freely available for the R statistical computing environment. In all models we used age as the explanatory variable and nine z scores above (i.e., attention control, shifting, working memory, rule-based and principle-based reasoning, rule-based and principle-based cognizance, and language) as criterion variables. We computed linear and segmented regression models for each process. We fit linear regression models of the form $y_i = a + bx_i + e_i$. These models provide estimates of direction and rate of developmental change for abilities which do not show signs of qualitative transitions with development. However, segmented regression models allow estimating if there are break points in development that may be taken to stand for qualitative changes in development. The F-test and Akaike information criterion (AIC) was used to decide if a linear or a segmented linear model best fits the age related patterning of performance on each criterion variable (Crawley, 2007).

The results of these analyses are summarized in Table 1 and illustrated in Fig. 4. It can be seen that five out of constructs (i.e., attention control, working memory, rule-based reasoning, principle-based cognizance, and language) were best modeled by segmented relationships, indicating an overlap of transitions from rule-based to principle-based thought. Specifically, change in working memory demarcated the beginning of rule-based thought at 9.08 years. Change in attention control occurred right in the middle of this phase at 9.85 years. Interestingly, transition from rule-based to principle-based thought was multiply demarcated. Specifically, it was indicated by transitions after the age of 10 years in rule-based reasoning (10.17 years) and language (10.36 years). Special attention is drawn to the U-shaped pattern of

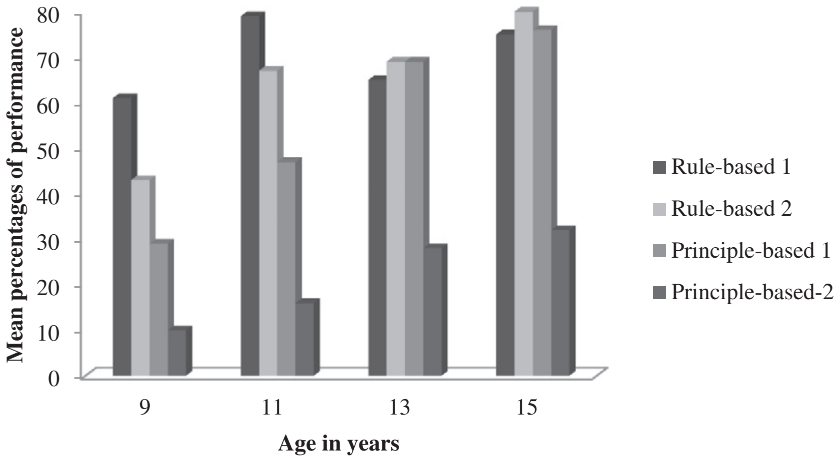


Fig. 2. Mean percentage attainment of tasks as a function of age and task level.

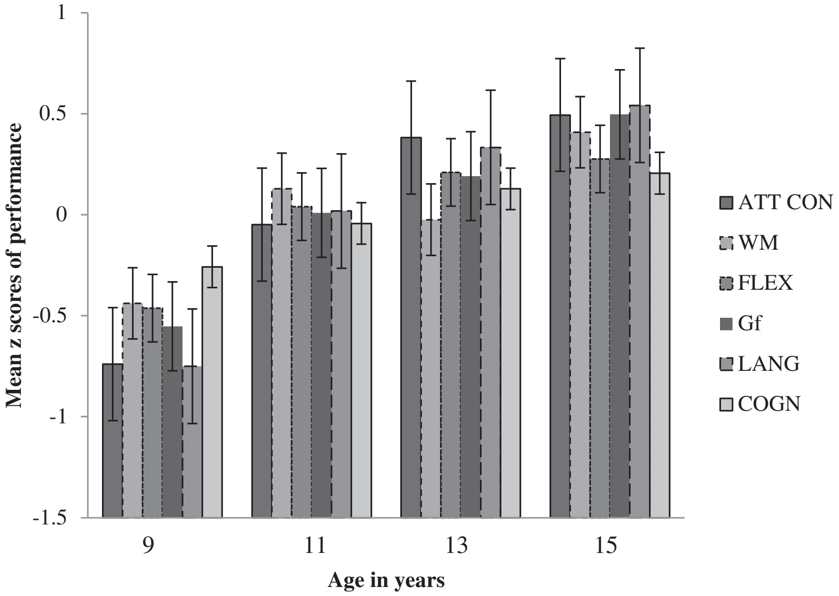


Fig. 3. Mean z scores across age and processes. Note: The symbols Att Con, Flex, and WM, Gf, Lang, and Cogn stand for attention control, flexibility of shifting, and working memory, fluid intelligence (or reasoning), language, and cognizance, respectively, in this and all other Figures and Tables following.

principle-based cognizance: it first dropped and then took off at 9.26 years, at about the same time with attention control. It may be noted here that analyzing performance at the level of a general index of reasoning and cognizance indicated linear growth. Therefore, on the one hand, in line with prediction 1ii, this pattern suggested that there was a major transition window between 10 and 11 years, and that developmental changes vary with process and phase. On the other hand, changes in some process may appear smoother than other processes, especially if represented by very inclusive indexes where variations in particular process are masked. These patterns will be discussed later on after we explore the relations between the various processes within and across phases. Structural equation modeling below will systematically explore the relations between processes within and across developmental phase.

3.3. Structural relations

3.3.1. Mapping the general factor

The patterns above suggested the operation of a common factor powerfully herding change in individual processes in the same direction. To capture this factor and specify its relation with each of the processes involved, a series of confirmatory factor models were tested on the whole sample. These models involved (i) the three attention control scores, (ii) the three shifting and the two VCCST scores addressed to flexibility, (iii) the three working memory scores, (iv) the four domain-specific reasoning scores, (v) the three language scores, and (vi) the four self-evaluation scores. The correlations used in this analysis are shown in Supplementary Table 2.

The first model involved a single factor directly associated with each of these 22 measures. Also, to control for possible task-specific random covariation between performance and self-evaluation, in this and all of the other models presented below, each of the error variances of the four self-evaluation scores were allowed to correlate with its corresponding performance score. The fit of this model was poor, χ^2 (201) = 622.48, p = 0.0001, CFI = 0.78, RMSEA = 0.10 (0.094–0.112), model AIC = 220.48, although all loadings were significant and moderate to high (0.3–0.9). Obviously, more dimensions than one underlie performance on the 22 variables.

To examine if the six sets of variables are organized according to their domain affiliation, the 22 variables were first subjected to an exploratory factor analysis with varimax rotation. This analysis extracted six factors (with eigenvalues > 1), accounting for 66% of the total variance. Each of the six sets of variables but language was related to a different factor. The three language scores loaded primarily on the cognitive factor and secondarily on the working memory factor. This analysis justified testing a confirmatory factor model where each set of scores was related to a different factor. A first version of the model assumed no relation between factors. The fit of this model was poor, χ^2 (201) = 657.14, p = 0.0001, CFI = 0.76, RMSEA = 0.11 (0.098–0.116), model AIC = 255.14. Allowing all domain-specific factors to correlate resulted in a model with excellent fit, χ^2 (186) = 215.11, p = 0.07, CFI = 0.98, RMSEA = 0.03 (0.00–0.04), model AIC = −156.89,

Table 1
Results from segmented regression models.

Measure	Breakpoint ± SE (years)		n	df	β_1 ± SE	LCI (95%)	UCI (95%)	AIC	R^2
Attention control	9.85	0.982	196	192	0.134 ± 0.038	0.058	0.209	3.13[a]	0.32
Shifting flexibility	10.01	1.061	196	192	0.054 ± 0.034	−0.013	0.121	2.76	0.15
Working memory	9.08	0.368	196	192	0.055 ± 0.034	−0.012	0.121	4.37[a]	0.16
Reasoning-R	10.17	0.761	196	192	0.155 ± 0.054	0.038	0.251	6.21[b]	0.34
Reasoning-P	15.08	0.050	196	192	−16.00 ± 12.71	−41.07	9.058	0.37	0.24
Cogn-R	14.34	0.377	196	192	−0.378 ± 0.413	−1.193	0.437	0.74	0.16
Cogn-P	9.26	0.547	196	192	0.127 ± 0.038	0.052	0.202	2.28[a]	0.07
Language	10.36	0.73	196	192	0.125 ± 0.035	0.055	0.194	6.51[b]	0.42

Note: linear models are not listed.

[a,b] Indicate models that were selected using F-test and stand for significance at .05 and .01, respectively. R and P stand for rule-based and principle-based reasoning or cognizance.

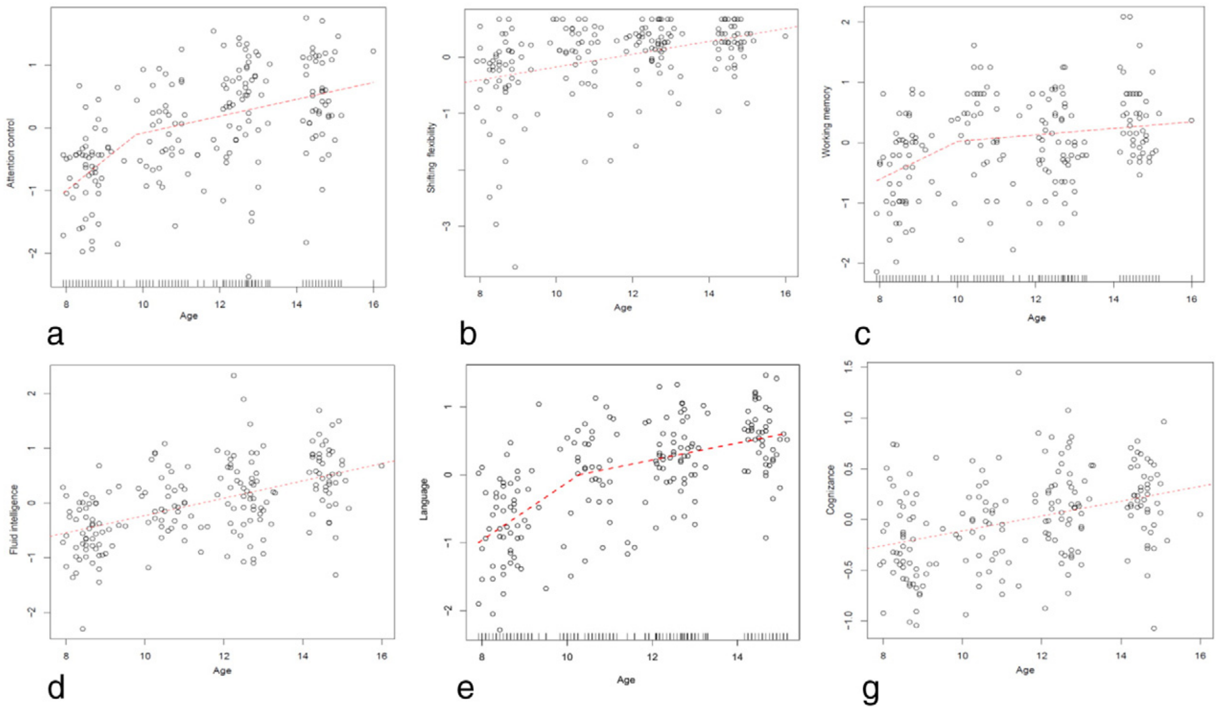


Fig. 4. Scatter plots and regression lines for the broken sticks models fit to the data. a) attention control measure, b) shifting flexibility, c) working memory, d) fluid intelligence, e) language ability, and f) cognizance.

$\Delta\chi^2$ (15) = 442.03, $p < 0.001$. Obviously, the strong relations between the domain-specific factors (all factor correlations were significant and most were high: mean R = 0.54) reflected the operation of a powerful common core.

In a fourth more parsimonious model a second-order factor related to all domain-specific factors was built in place of between-factor correlations. The fit of this model was good, χ^2 (217) = 380.04, p = 0.0001, CFI = 0.92, RMSEA = 0.06 (0.051–0.072), model AIC = −53.96, and significantly better than both, the first ($\Delta\chi^2$ (16) = 242.44, $p < 0.001$) and the second model above ($\Delta\chi^2$ (16) = 277.10, $p < 0.001$). However, it was weaker than the oblique model ($\Delta\chi^2$ (31) = 164.93, $p < 0.001$). Obviously, in line with the second prediction, both the domain-specific factors and the general factor are needed to account for performance on the various batteries. However, there is more in the relations between the factors than what is captured by the second-order general factor. According to the third prediction, age may independently contribute to the relations between processes. To test this assumption, a fifth model was tested where the second-order common factor was regressed on age. The fit of this model was excellent, χ^2 (216) = 264.30, p = 0.01, CFI = 0.98, RMSEA = 0.03 (0.016–0.047), model AIC = −167.70, and significantly better than the fourth model ($\Delta\chi2$ (1) = 115.74, $p < 0.001$). Although marginally weaker than the oblique (third) model ($\Delta\chi2$ (30) = 49.10, $p > 0.01$), this model is preferable because it is more parsimonious. It can be seen in Fig. 5 that age accounted for half of the variance of G (0.70). The rest was independent of age. We will further explore these relations by several other models.

To explore the possible differentiation of these relations in the three developmental phases investigated here, the model including the G-age relation was tested in 3-group model which included the (i) 9- and 11-, (ii) 11- and 13-, and (iii) 13- and 15-years old participants. The three groups may highlight relations between processes in (i) the second phase of rule-based thought, (ii) the first, and (iii) the second phase of principle based thought, respectively. The reader might object that the second group was composed of participants already included in the first (11-year olds) and the third group (13-year olds). Admittedly, the disadvantage of this manipulation is that it technically inflates degrees of freedom in the model without the compensation that would result from a larger and thus more representative sample. The advantage is that it allows testing relations within a common analysis where all age phases are represented and subjected under the same model constraints, simulating reality as much as possible in the context of a cross-sectional study. An alternative solution to this problem would be to model the data separately in a 2-group model which would involve groups 1 and 3 above and in a single group model that would involve group 2. In fact, this solution was tested and found to have the same results with the first solution involving all groups in the same model. We opted to present the first solution because it is stricter and more parsimonious.

The first model was highly constrained. Specifically, (i) all relations between scores with their respective factors, (ii) all relations of the first-order factors with the second-order G factor, (iii) the relation between age and the G factor, and (iv) all score measurement errors were constrained to be equal across the three groups. Therefore, this model implements the assumption that the three groups are completely identical. The fit of this model was below optimal, χ^2 (742) = 1139.13, p = 0.001, CFI = 0.860, RMSEA = 0.075 (0.065–0.083), model AIC = −344.87. The Lagrange test for releasing constraints (Bentler, 2006) suggested that the age-G relation and the relation between some of the first-order factors with G did not hold. To test the relative contribution of each of these constraints to model fit, several models were tested in a step-wise fashion. Specifically, at first, only the equality constraint of the age-G relation was released. Model fit, χ^2 (740) = 1124.25, p = 0.001, CFI = 0.865, RMSEA = 0.073 (0.064–0.082), model AIC = −355.75 improved significantly, ($\Delta\chi^2$ (2) = 14.88, $p < 0.001$), suggesting that the age-G relation varies across phases. At a second run, the constraints of the equality of the relations between the attention control and the cognitive flexibility first-order factors with G were released. Releasing these constraints resulted in a further significant improvement of the model fit, χ^2 (736) = 1106.41, p = 0.001, CFI = 0.870, RMSEA = 0.072 (0.063–0.080), model AIC = −365.59, ($\Delta\chi^2$ (4) = 17.85, $p < 0.005$). However, releasing the constraints of equality between working memory, reasoning, and language, on the one hand, and G on the other did not significantly improve the model fit, χ^2 (730) = 1098.16, p = 0.001, CFI = 0.870, RMSEA = 0.072 (0.063–

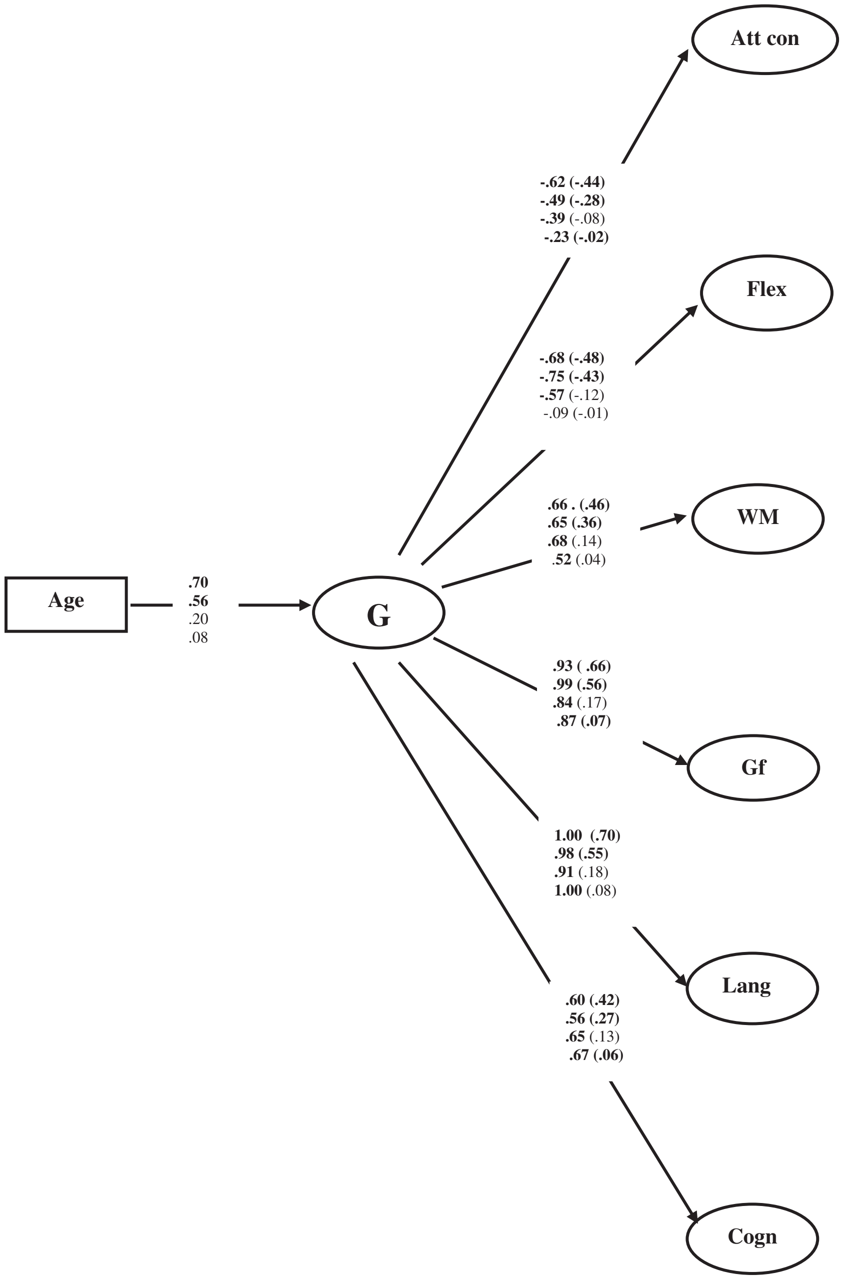


Fig. 5. The hierarchical model involving all process-specific factors and the second-order factor standing for g. Note: The first value in each set stands for the total sample and the other three values for each age phase. Loadings in parenthesis stand for relations after regressing G on age. Significant relations are shown in bold.

0.081), model AIC = −361.84, ($\Delta\chi^2$ (6) = 8.24, $p > 0.010$). Finally, all equality constraints involving the attention control and the cognitive flexibility measures were released, to model the assumption that the operation of these measures changes across developmental phases. Releasing these constraints resulted in a very large improvement of the model fit, rendering the model perfectly acceptable, χ^2 (705) = 977.98, p = 0.001, CFI = 0.902, RMSEA = 0.063 (0.053–0.072), model AIC = −432.02, ($\Delta\chi^2$ (25) = 120.10, $p < 0.001$). The relations found by the last model are presented in Fig. 5. The correlations between the variables in each age phase are shown in Supplementary Tables 3–5.

There are some interesting trends in these models. First, the model applied on the whole sample suggested that all processes are highly related to G (all varied from 0.6–1.0). It is also notable that G was primarily marked by reasoning (0.93) and language (1.0) rather than by processing efficiency (all ~0.6). Second, half of the variance of G was accounted for by age variation (0.70). Although high, this effect leaves an equally large room for the operation of other factors beyond pure age progression. In fact, the systematic decrease of age-G relations with developmental phase (0.55, 0.21, and 0.08 across the three successive phases, respectively) suggests that individual differences in G tend to become independent of sheer progression of age. Shift of executive control from handling mental focus to handling representationally laden processes is an important factor in this respect. One might object that these patterns are caused by the fact that attention control and cognitive flexibility approach ceiling after the age of 11 years whereas all representational processes continue to improve. This is technically

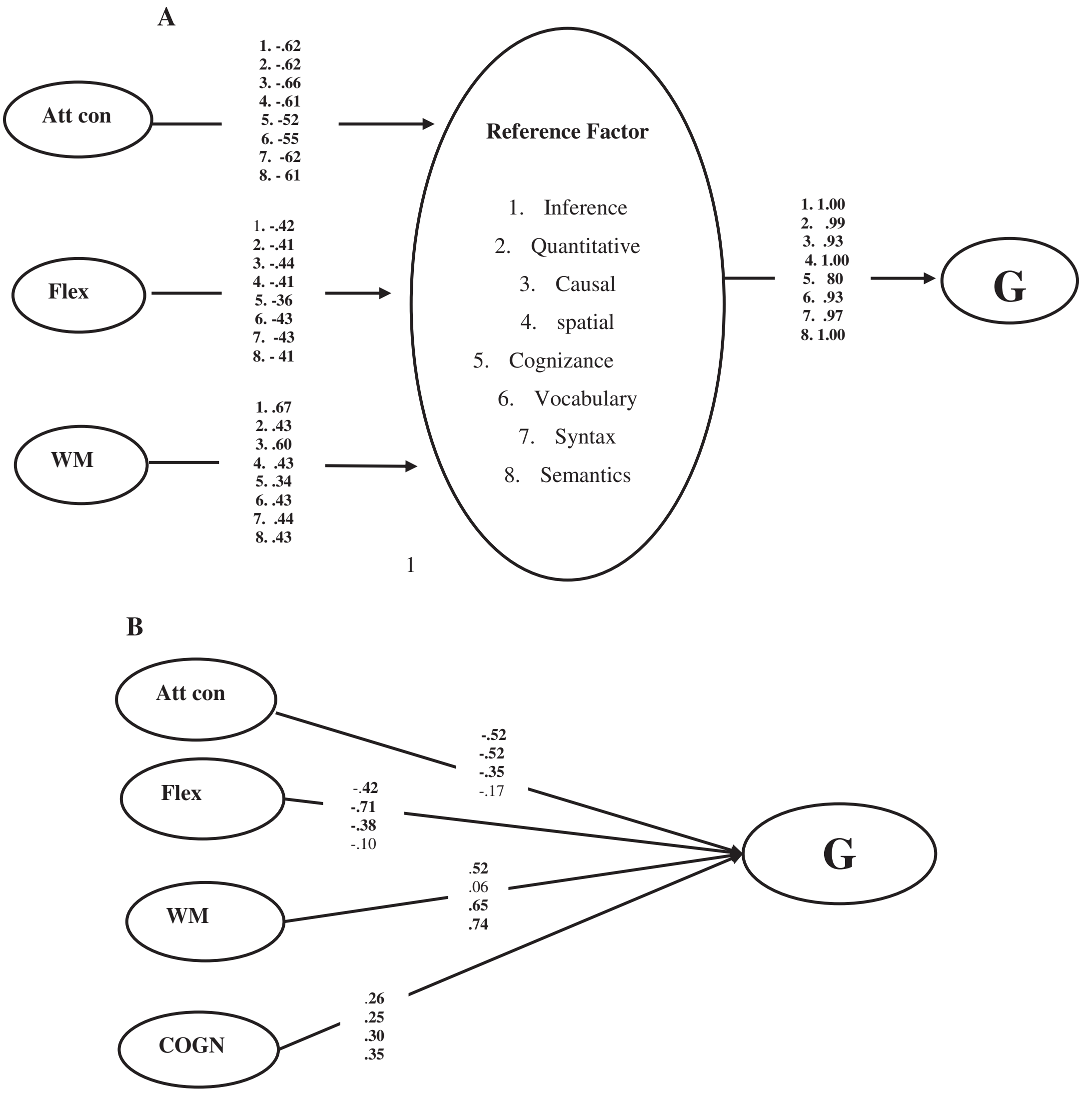


Fig. 6. A Structural relations between G and each of the reference factors and each of the reference factors with attention control, cognitive flexibility, and working memory. Note: All reference (first-order factors) but one were regressed on G and G was regressed on the reference factor left out in eight successive runs of the model. Each reference factor was regressed on the three executive factors. All CFIs >0.91. All relations were significant. B Relations between G, executive processes, and cognizance at the level of the total sample and the three age phases. Note: G was regressed on attention control and the residuals of the other three factors. Significant relations are shown in bold.

justified. However, their relatively early ceiling points to a substantive aspect of intellectual development: Mental control, having mastered attentional and mental focus extends to command the orchestration of inferential and representational processes as such.

3.3.2. *Is any process a privileged proxy for AACog?*

To examine the relative importance of each specific process vis-à-vis the common core, a different approach to modeling was adopted. Specifically, several models were tested which aimed to test prediction #2 about the possibly privileged role of reasoning or language. In the sake of this aim, there were four first-order factors standing for each of the four reasoning domains (i.e., inductive and deductive, quantitative, causal, and spatial reasoning) and three first-order factors standing for the three aspects of language (i.e. vocabulary, syntax, and semantics) in addition to the factors standing for attention control, shifting, working memory, and cognizance,.

To test if any of the domain-specific factors has a privileged relation with cognition a second-order factor was created which was related to all of these seven factors *but one*. The second-order factor was regressed on the domain-specific factor left out. Therefore, each of the domain-specific factors was lifted up to the status of a reference factor or a proxy that may speak about the identity of the common factor. Obviously, a high relation between a reference factor and the common factor would indicate that the common factor carries much of the constituent properties of the reference factor. In turn, the reference factor was regressed on attention control, cognitive flexibility, and working memory. This manipulation would highlight if the reference factor behaves as the general factor it stands for, vis-à-vis the various predictors. The fit of all models was good (All CFIs > 0.91 and all RMSEAs < 0.06).

The structural relations generated by successive runs of this model are shown in Panel A of Fig. 6. It is noted, first, that the common factor was very powerful as all relations between this factor and each of the domain specific cognitive or language factors were very high (all > 0.70). Second, the relation between the reference factor and the common factor was always very high regardless of which of the eight domain-specific factors was lifted to the status of the reference factor, although the size of this relation varied to a certain extent (between 0.80 (cognizance) to 1 (inference, spatial, and semantics). Obviously, these results do not support prediction 2ii that syntax or any other domain-specific factor is a privileged representative of the common core. Rather, in line with prediction #2iii, these results suggest that all domains contain the common core to a large extent so that any one of them can reliably stand for it. This interpretation is also supported by the fact that all reference factors were significantly and about evenly related to all three executive control factors (varying between 0.4 and 0.6).

To specify the direct relations between the general cognitive factor and each of the three executive control factors and cognizance, a second set of models were tested where all four domain-specific reasoning and all three domain-specific language factors were related to the second-order common factor. This factor was regressed on attention control, and *the residuals* of shifting, working memory and cognizance. Given the cascade relation between the factors, this manipulation is considered able to purify the effect of each factor from possible influences coming from other lower-order factors it is related to (Bentler, 2006). The model was first tested under the assumption of complete across age groups equality constraints (involving indicator-factor relations, first-order-second-order factor relations, and G-factor or residual structural relations. The model fit well, (χ^2 (1488) = 1894.03, p = 0.001, CFI = 0.88, RMSEA = 0.053 (0.045–0.060, model AIC = −1081.97). However, in line with the findings above about differences between age groups, the Langrage test for releasing constraints suggested that most of first-order-second-order factor relations and the G-factor or residual structural relations did not hold. Releasing these constraints resulted in a significant improvement of model fit, χ^2 (1458) = 1798.86, p = 0.001, CFI = 0.90, RMSEA = 0.049 (0.041–0.056), model AIC = −1117.14, $\Delta\chi^2$ (30) = 95.17, $p < 0.001$).

Panel B of Fig. 6 summarizes the trends revealed by these models. On the one hand, the effects of both, attention control (i.e., −0.52, −0.35, and −0.17, for the three age groups, respectively) and shifting (i.e., −0.71, −0.38, and −0.10, for the three age groups, respectively), decreased across the three age phases. On the other hand, the effects of working memory (i.e., 0.06, 0.65, and 0.74, for the three age groups, respectively) and cognizance (i.e., 0.25, 0.30, and 0.35, for the three age groups, respectively) increased. Therefore, there is a shift from executive processes related to control of attentional and mental focus to processes directly related to the organization of representation and inference as such. This change is fully established at the end of principle-based cognition, when the role of working memory and cognizance strengthened further while both attention control and shifting faded out almost completely. Obviously, these patterns are consistent with our third prediction.

3.3.3. Evaluation of the cascade model

The general factor is a capsule index of the relations between the various processes. To decompose these relations, the second-order general factor was dropped and the hierarchical model above was transformed into a structural equation model where direct relations between the first-order factors (and age) were examined. Specifically, a simplex model was first tested assuming that there is a hierarchical relation running bottom-up from simpler to more complex processes as specified by the cascade model. To implement this assumption, the chain of regressions was as follows: age ➔ attention control (−0.64) ➔ shifting (0.58) ➔ working memory (−0.89) ➔ reasoning (0.87) ➔ language (0.98) ➔ cognizance (0.60). This model was first tested on the whole sample and was found to fit well, χ^2 (218) = 360.90, p = 0.001, CFI = 0.93, RMSEA = 0.058 (0.047–0.068), model AIC = −75.10.

One might claim that if the common core is responsible for the relations running through the cascade, the direction of the relations would be irrelevant. A strict test of this objection would be to invert the direction of the relations running through the cascade. The inverse chain of regressions was as follows: age ➔ cognizance (0.50) ➔ language (0.67) ➔ reasoning (0.97) ➔ working memory (0.84) ➔ shifting (−0.84) ➔ attention control (0.48). The fit of this model, although also within range of acceptability, was significantly weaker than the classical cascade model above, χ^2 (218) = 403.01, p = 0.001, CFI = 0.91, RMSEA = 0.066 (0.055–0.075), model AIC = −32.99, $\Delta\chi^2$ = 42.11. However, the difference in fit between the two models resulted from the difference of the relation of age with attention control in the first model and cognizance in the second model (−0.64 vs. 0.50, z = −44.83, $p < 0.01$). No other relation was significantly different in the two models (all z values < 0.6, all p values >0.05). Therefore, the common core is always present, binding relations between individual processes regardless of direction. This model is shown in Fig. 7.

It might be the case, however, that the strength and direction of relations varies with phase to indicate the gradual expansion of the core as it integrates higher level processes into its operation. That is, in line with prediction #3, the gradual expansion of the core would be reflected into a gradual shift of strength in the relations between processes with age phase: the later the phase the stronger the relations between processes residing higher in the cascade would have to be. To test this assumption, the cascade model was tested on the three age phases in the fashion described above.

To increase the resolution of the model at the level of more complex processes we created separate reasoning and cognizance factors for rule- and principle-based tasks. Specifically, a set of three mean scores were computed for rule-based reasoning tasks and another set of three mean scores for principled based tasks. Each of the three scores standing for rule based processes and each of the three scores standing for principle-based processes involved items representing all tasks across the four domains. The rule-based and the principle-based cognizance scores included the evaluations of success and difficulty of performance on the items involved into each corresponding reasoning performance score. Thus, this model involved two reasoning and two cognizance factors, one for rule-based and one for principle-based processes, replacing their corresponding general reasoning and general cognizance factor of the previous model.

At a first run, the following cascade relations were built into the model: age ➔ attention control ➔ cognitive flexibility ➔ working memory ➔ rule based reasoning ➔ language, rule-based cognizance, and principle-based reasoning ➔ principle-based cognizance. The model was tested in a 3-group phase-specific set up as specified above. At the first run, all score-factor relations and all factor-factor cascade relations were constrained to be equal across groups. Given that this is a very strict model, the fit was acceptable, χ^2 (966) = 1341.82, p = 0.001, CFI = 0.89, RMSEA = 0.064 (0.055–0.072), model AIC = −590.182. However, according to the Lagrange test for releasing

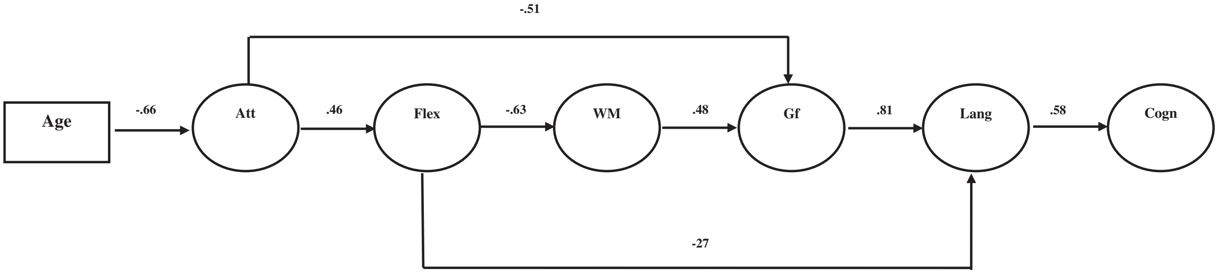


Fig. 7. The cascade model fit on the total sample. All relations are significant.

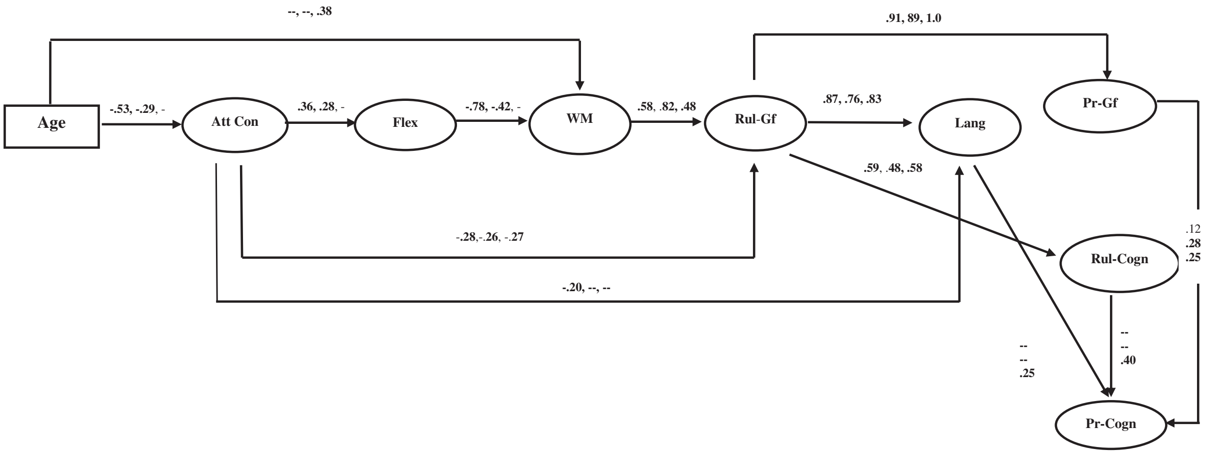


Fig. 8. The cascade model fit on the three age phases. Note: Reasoning and cognizance were represented by level specific factors standing for rule-based and principle-based thought. Rul and Pr stand for rule-based and principle based, respectively. Significant relations are shown in bold.

constraints, several of the constraints of between-factors relations did not hold. Thus, all constraints involving cascade relations were released. This change resulted in a significant improvement of the model fit, χ^2 (950) = 1299.80, p = 0.001, CFI = 0.90, RMSEA = 0.062 (0.053–0.070), model AIC = −600.198, ($\Delta\chi^2$ (16) = 42.02, $p < 0.001$). Also, the Lagrange test for adding parameters suggested that, in addition to the cascade relations above, there are direct relations between processes that are specific to each age group. Adding these relations resulted in a further improvement of the model fit, χ^2 (1458) = 1798.86, p = 0.001, CFI = 0.90, RMSEA = 0.049 (0.041–0.056, model AIC = −1117.14, ($\Delta\chi^2$ (8) = 64.22, $p < 0.001$). This is the model shown in Fig. 8.

The relations between age, attention control, shifting, and working memory were very similar to the model shown in Fig. 6B. These relations decreased systematically across the three age groups. The only notable differences between the present models and the models above are concerned with the relations between the reasoning and the cognizance factors. Specifically, in the 9–11 years phase, rule-based reasoning and cognizance were highly related but principle-based reasoning and cognizance were not related. In the two next phases both relations were significant. Also, the two cognizance factors were not related in the earlier phases but they were highly related (0.40) in the older phase. Also, in the older age phase there was a significant relation between language and principle-based cognizance (0.25). Therefore, in line with prediction #3i, there was a shift from executive processes related to control of attentional and mental focus to processes directly related to the organization of representation and inference as such.

3.3.4. *What is differentiated with growth?*

To specify the ability/age differentiation hypothesis a model recently proposed by Tucker-Drob (2009) was employed. This is a structural equation model allowing testing the possible differentiation of abilities with increasing g and/or development. This model specifies how abilities relate to g, age, a factor standing for possible differentiation of abilities from g according to increasing g, and a factor standing for a possible differentiation of abilities as a function of age. Technically, a standardized measure of each ability is regressed on a common factor standing for g, on age, on quadratic g, and on the age × g product to stand for the relations specified above, respectively. This model was tested on the whole sample and also on each of the three age groups specified above in a step-wise fashion. That is, at a first run, the eight ability-specific indexes used in the model above were regressed on g and age. The second run involved two alternative models: (i) in the first, the ability differentiation quadratic g index was also included in each equation; (ii) in the second, quadratic g was dropped and age differentiation (g × age) factor was used. Finally, all indexes were included in the model.

The results of these models are summarized in Table 2. Step-wise comparisons of the successive models in each age group suggest that adding either the ability differentiation factor (quadratic g) or the age (age × g) differentiation factor caused a large improvement of model fit (decrease of AIC was in the range of hundreds). It is noted, however, that all ability differentiation models fit better than the age differentiation models. Also, using both differentiation factors did not cause any further improvement of model fit; in fact, the fit of these models was weaker than the fit of the models involving only the ability differentiation factor. Therefore, in line with prediction 3ii, at a global level, the data supported the operation of ability differentiation; age differentiation exists but it is largely co-extensive with ability differentiation.

However, "it is important to inspect the direction and statistical significance of each of the terms in order to evaluate whether the ability differentiation and age differentiation hypotheses were supported. To accept such support, the parameters should be in directions indicative of lower loadings at high ability levels, [and] lower loadings with increasing childhood age …. Moreover, the effects should not be isolated to a single broad ability, but should instead be statistically significant and consistent in direction for multiple abilities." (Tucker-Drob, 2009, p. 17). Inspection of Table 2 suggests that, in the whole sample, attention control, shifting, and working memory appeared to undergo both ability and age differentiation. Working memory appeared to undergo ability differentiation. Principle-based reasoning demonstrated age-specific differentiation but in the opposite direction, suggesting de-differentiation or strengthening of the relations of principle-based thought with g.

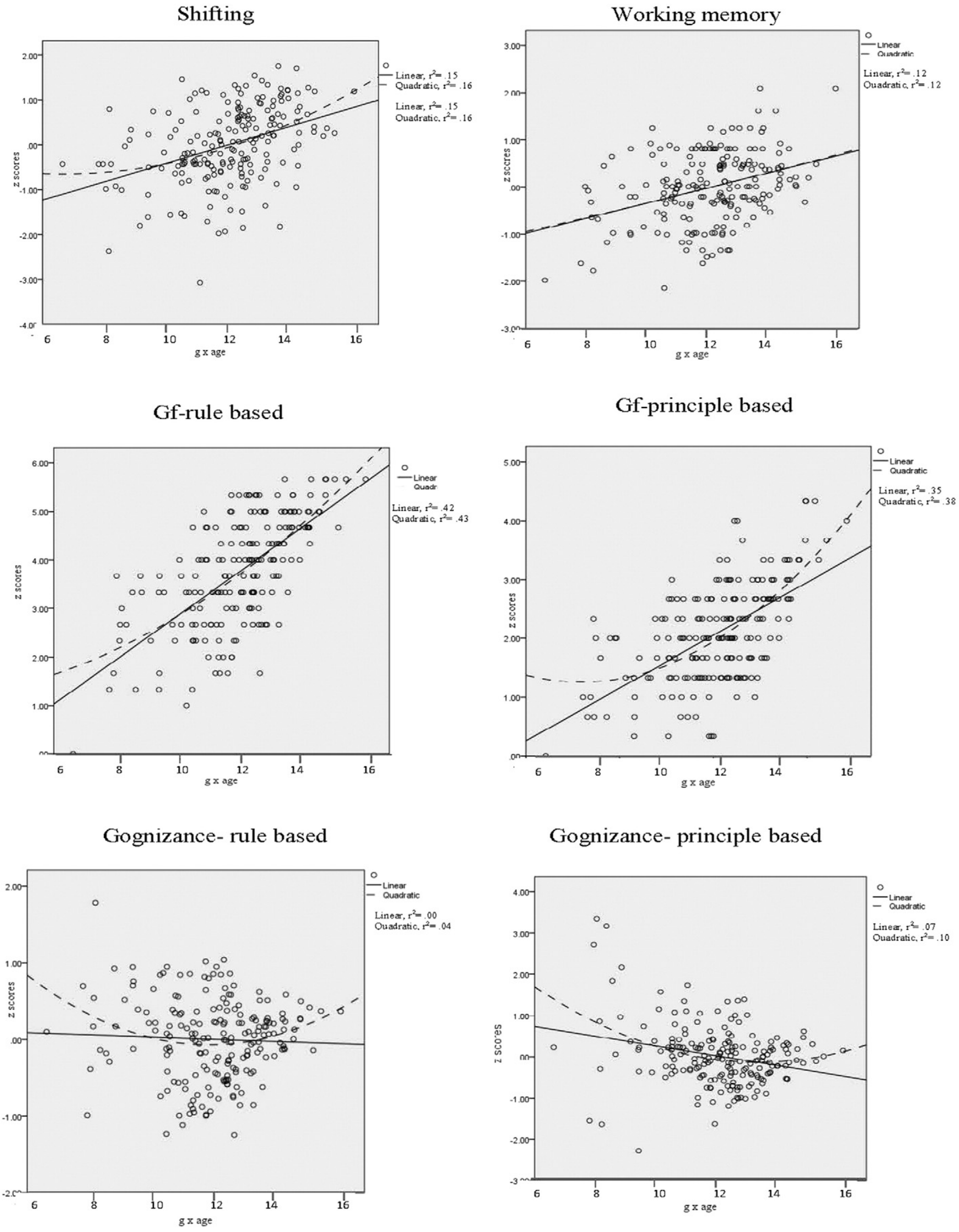
To obtain a stricter test of the possible interaction between changes in ability and changes in age, we tested, on the level of the whole sample, three alternative versions of the model above where all differentiation factors were freely estimated. Specifically, following Cheung, Harden, and Tucker-Drob (2015), in the first alternative, we constrained the effect of the age × g interaction on each ability to be proportional to the corresponding g-ability relation. In the second alternative, we constrained the two interaction coefficients (quadratic g and g × age) to be equal across abilities. In the third alternative, we fixed all interaction coefficients at zero. At the one extreme, finding that the first model where all main and interaction factors were freely estimated fits the data better than the other models would imply that the strength of influence of the various factors of ability vary with changing ability and/or age. At the other extreme, finding that the model with no interactions fit the data better would imply a uniform (linear effect) of changes in g

Table 2
Models testing ability and age differentiation across age phases and the total sample.

Ability	Linear model		Ability differentiation model		Age modification model		Nonlinear + age modification model		
	λ1 g	λ1(std)	λ1 g	λ2 g2	λ1 g	λ3 age .g	λ1 g	λ2 g2	λ3 age .g
Whole sample									
Attention	**0.16**	**0.20**	**0.19 (0.05–0.33)**	*0.06 (−0.02–0.14)*	**0.35 (0.07–0.62)**	0.08 (−0.01–0.17)	**0.20 (0.06–0.34)**	0.04 (−0.05–0.13)	**0.05 (−0.01–0.10)**
Shifting	**0.24**	**0.39**	**0.25 (0.12–0.39)**	**−0.13 (−0.26–0.00)**	**0.50 (0.16–0.83)**	**−0.17 (−0.30–0.03)**	**0.24 (0.12–0.35)**	**−0.10 (−0.19–0.01)**	**−0.08 (−0.13–−0.03)**
WM	**0.30**	**0.39**	**0.29 (0.14–0.45)**	**−0.08 (−0.17–0.01)**	**0.59 (0.26–0.91)**	*−0.08 (−0.21–0.06)*	**0.28 (0.14–0.42)**	**−0.08 (−0.17–0.02)**	−0.03 (−0.10–0.04)
Gf-R	**0.86**	**0.76**	**0.80 (0.64–0.98)**	0.01 (−0.16–0.16)	**1.57 (0.94–2.2)**	−0.02 (−16–0.11)	**0.80 (0.64–0.97)**	−0.02 (−0.15–0.11)	0.01 (−0.06–0.08)
Gf-P	**0.54**	**0.64**	**0.55 (0.38–0.72)**	0.07 (−0.06–0.20)	**1.36 (1.03–1.49)**	0.06 (−0.05–0.16)	**0.55 (0.40–0.70)**	0.03 (−0.09–0.16)	**0.04 (−0.01–0.10)**
Language	**0.44**	**0.58**	**0.45 (0.33–0.57)**	−0.04 (−0.12–0.05)	**0.85 (0.46–1.24)**	**−0.09 (−0.19–0.02)**	**0.43 (0.33–0.54)**	−0.03 (−0.09–0.03)	*−0.03 (−0.08–0.01)*
Cogn-R	**0.23**	**0.44**	**0.21 (0.10–0.32)**	0.08 (−0.06–0.22)	**0.40 (0.10–0.70)**	0.02 (−0.09–0.12)	**0.21 (0.09–0.33)**	0.06 (−0.07–0.20)	0.01 (−0.04–0.06)
Cogn-P	0.09	0.12	0.10 (−0.06–0.26)	−0.05 (−0.20–10)	0.15 (−0.19–0.49)	*−0.05 (−0.20–0.10)*	0.08 (−0.09–0.25)	−0.04 (−0.20–0.13)	−0.02 (−0.11–0.07)
AIC	2904.38		2890.35		2884.42		2875.03		
9–11									
Attention	0.14	0.18	*0.14 (−0.07–0.35)*	0.05 (−0.13–0.23)	*0.10 (−0.06–0.26)*	**0.18 (0.05–0.30)**	0.11 (−0.07–0.29)	0.04 (−0.09–0.18)	0.18 (0.03–0.31)
Shifting	0.44	**0.61**	**0.42 (0.20–0.65)**	**−0.20 (−0.35–−0.05)**	**0.40 (0.08–0.73)**	0.01 (−0.21–0.23)	**0.43 (0.20–0.66)**	**−0.20 (−0.34–−0.05)**	−0.01 (−0.20–0.17)
WM	0.37	**0.46**	**0.34 (0.13–0.55)**	**−0.19 (−0.36–−0.01)**	**0.33 (0.06–0.60)**	0.10 (−0.07–0.27)	**0.33 (0.13–0.52)**	−0.19 (−0.32–0.06)	*0.10 (−0.06–0.27)*
Gf-R	0.93	**0.85**	**0.82 (0.61–1.02)**	0.02 (−0.20–0.24)	**0.88 (0.65–1.11)**	0.06 (−0.07–0.20)	**0.82 (0.58–1.06)**	0.00 (−0.18–0.19)	0.07 (−0.10–0.25)
Gf-P	0.57	**0.76**	**0.50 (0.31–0.70)**	0.07 (−0.12–0.27)	**0.53 (0.35–71)**	0.03 (−0.12–0.19)	**0.51 (0.31–0.70)**	0.06 (−0.11–0.23)	0.02 (−0.16–0.21)
Language	0.59	**0.78**	**0.56 (0.41–0.71)**	−0.04 (−0.18–0.10)	**0.53 (0.34–0.72)**	*0.07 (−0.03–0.19)*	**0.55 (0.40–0.70)**	−0.05 (−0.16–0.06)	0.06 (−0.05–0.17)
Cogn-R	0.25	**0.44**	**0.22 (0.05–0.40)**	0.15 (−0.08–0.38)	**0.22 (0.01–0.43)**	0.08 (−0.07–0.24)	**0.21 (0.03–0.38)**	0.12 (−0.07–0.32)	0.06 (−0.13–0.26)
Cogn-P	0.19	**0.25**	**0.16 (−0.06–0.39)**	−0.08 (−0.29–0.12)	**0.18 (−0.04–0.40)**	0.00 (−0.22–0.22)	**0.17 (−0.05–0.40)**	−0.06 (−0.26–0.14)	0.01 (−0.21–0.22)
AIC	1842.36		1516.05		1538.15		1517.96		
11–13									
Attention	**0.23**	**0.38**	**0.19 (−0.12–0.41)**	−0.12 (−0.40–0.16)	**0.23 (0.04–0.41)**	−0.04 (−0.20–0.12)	**0.19 (−0.03–0.40)**	−0.11 (−0.34-,12)	−0.06 (−0.24–0.12)
Shifting	**0.21**	**0.50**	**0.20 (0.03–0.36)**	*−0.13 (−0.33–0.06)*	**0.21 (0.01–0.40)**	−0.07 (−0.23–0.09)	**0.18 (0.02–0.34)**	−12 (−0.32–0.07)	−0.06 (−0.19–0.07)
WM	**0.37**	**0.64**	**0.34 (0.12–0.56)**	**−0.20 (−0.37–0.03)**	**0.37 (0.15–0.59)**	−0.05 (−0.26–0.16)	**0.32 (0.10–0.53)**	−0.24 (−0.46–−0.01)	−0.04 (−0.23–0.16)
Gf-R	**0.84**	**1.0**	**0.84 (0.64–1.04)**	−0.12 (−0.42–0.18)	**0.87 (0.67–1.07)**	−0.04 (0.23–0.15)	**0.86 (0.65–1.06)**	−0.12 (−0.40–0.15)	0.02 (−0.18–0.22)
Gf-P	**0.49**	**0.82**	**0.53 (0.33–0.72)**	0.06 (−0.24–0.36)	**0.49 (0.28–0.70)**	−0.02 (−0.20–0.16)	**0.50 (0.31–0.70)**	0.06 (−0.28–0.39)	0.04 (−0.18–0.26)
Language	**0.45**	**0.94**	**0.41 (24–0.60)**	**−0.21 (−0.42–0.00)**	**0.45 (30–0.60)**	**−0.16 (−0.32–00)**	**0.39 (0.23–56)**	**−0.18 (−0.30-−0.06)**	**−0.14 (−0.28–−0.02)**
Cogn-R	**0.26**	**0.64**	**0.22 (0.02–0.42)**	−0.03 (−0.34–0.28)	**0.24 (0.02–0.46)**	*−0.09 (−0.21–0.04)*	**0.20 (0.00–0.41)**	−0.01 (−0.26–0.27)	−0.07 (−0.22–0.08)
Cogn-P	**0.19**	**0.35**	**0.16 (−0.02–0.35)**	−0.10 (−0.28–0.08)	**0.18 (−0.02–0.38)**	−0.02 (−0.18–0.15)	*0.14 (−0.05–33)*	−0.11 (−0.36–0.14)	−0.02 (−0.18–0.14)
AIC	1705.79		1400.18		1414.34		1398.93		
13–15									
Attention	**0.21**	**0.28**	**0.17 (0.00–0.33)**	−0.04 (−0.21–0.12)	**0.19 (0.01–0.39)**	0.04 (−0.14–0.23)	**0.19 (0.02–0.37)**	−0.04 (−0.16–0.07)	0.04 (−0.12–0.20)
Shifting	0.04	0.12	0.04 (−0.06–0.14)	0.02 (−0.06–0.10)-	0.04 (−0.07–0.15)	−0.02 (−0.12–0.08)	0.04 (−0.06–0.15)	0.02 (−0.06–0.10)	−0.03 (0.12–0.05)
WM	**0.24**	**0.36**	**0.20 (0.04–0.36)**	0.08 (−0.23–0.06)	**0.22 (0.04–0.41)**	*−0.11 (−0.29–0.06)*	**0.20 (0.03–0.36)**	−0.09 (−0.22–0.04)	*−0.10 (−0.25–0.06)*
Gf-R	**0.88**	**0.94**	**0.89 (0.84–0.95)**	**−0.17 (−0.23–−0.11)**	**0.82 0.58–1.06)**	−0.07 (−0.29–0.16)	**0.89 (0.82–0.96)**	**−0.18 (−0.26–−0.10)**	−0.02 (−0.09–0.05)
Gf-P	**0.60**	**0.76**	**0.53 (0.35–71)**	0.03 (−0.08–0.15)	**0.56 (0.36–0.76)**	0.07 (−0.12–0.26)	**0.57 (0.36.78)**	0.03 (−0.11–0.16)	0.08 (−0.08–0.25)
Language	**0.32**	**0.66**	**0.27 (0.17–0.38)**	**−0.07 (−0.16–0.02)**	**0.29 (0.16–0.42)**	0.01 (−0.12–0.15)	**0.28(0.17–0.38)**	**−0.08 (−0.17–0.02)**	0.03 (−0.08–0.14)
Cogn-R	**0.22**	**0.55**	**0.29 (0.12–0.34)**	−0.04 (−0.11–0.04)	**0.20 (0.06–0.34)**	0.03 (−0.11–0.16)	**0.23(0.13–0.33)**	−0.04 (−0.13–0.04)	0.02 (−0.08–0.12)
Cogn-P	0.02	0.04	0.03 (−0.15–0.22)	0.03 (.−0.09–0.16)	0.01 (−0.22–0.24)	−0.12 (−0.39–0.15)	0.02–0.17–0.21)	0.06 (−0.09–0.22)	−0.09 (−0.32–0.13)
AIC	1608.96		1303.41		1325.03		1312.35		

Note: Numbers are estimates in all cases but the standardized relations in the linear model. (Confidence intervals in parenthesis).
Significance: Bold: $p < 0.05$; Italics: $p < 0.10$.

changes in specific abilities, A better fit of any of the two intermediate models would imply a special effect of the interaction concerned. Notably, the fit of the three alternative models specified above was weaker (AIC = 3081.51, 2887.74, and 2887.74, respectively) than the first model (AIC = 2875.03). Therefore, it is suggested that g as a driver of change in specific abilities operates differently at different age phases.



Shifting

Working memory

Gf-rule based

Gf-principle based

Gognizance- rule based

Gognizance- principle based

Fig. 9. Relations between each process and the interaction between g and age (g × age in the models shown in Table 2). Age is also shown for indicative purposes.

To zoom on in the operation of g in each of the three age phases, the first model above was tested separately each phase. In line with the findings of the other models presented above, in the 9–11 years phase only three abilities (attention, shifting, and WM) undergo differentiation with increasing g; attention control also undergoes age differentiation. In the 11–13 years phase working memory undergoes ability differentiation and language undergoes both ability and age differentiation. In 13–15 years phase only rule-based reasoning undergoes age differentiation.

These patterns, which are illustrated in Fig. 9, are consistent with prediction 3ii and the trends suggested by the cascade models. That is, differentiation of abilities from g is a developmental phenomenon from childhood to adolescence as it varies with developmental phase. Specifically, the various aspects of processing efficiency and executive control are more amenable to differentiation in the present age period than inferential abilities, probably reflecting their relative automation by the beginning of principle-based at 11–13 years of age. Overall, these abilities seem to differentiate more in the last phase of rule-based reasoning than later. Interestingly, language and reasoning, when they differentiate with ability or age, do so in the cycle of principle-based thought rather than earlier. In conclusion, in line with prediction 3ii inferential abilities do not differentiate with increasing g or age in the phases studied here because representation possibilities are reformed in these phases, in a sense re-invigorating the power of g.

4. Discussion

The findings of this study came generally in line with predictions. The cognitive tasks were solved at the age phases expected. Between age differences were generally in line with the phase concerned. Some processes developed fast and consolidated by the age of 11 years (i.e., executive processes) and others continued to develop until the age of 15 years (i.e., reasoning and cognizance). In fact, piecewise linear modeling suggested that each of the three phases investigated here are somehow marked by a specific point of shift related to a specific process. Specifically, attainment of the second phase of rule-based reasoning was marked by a change in working memory at the age of 9 years. This is in line with earlier research suggesting that working memory is the dominant marker of this phase. Interestingly, the break point of attention control was found at about the age of 10 years, when this phase consolidates and transition to principle-based thought begins. At about the same time principle-based cognizance started to take off. One might expect these break points at 11 rather than at 10 years. This divergence, however, might suggest changes in underlying control processes and related awareness that will surface up a little later as explicitly used principles. Finally, it is interesting that principle-based thought was marked by a break in the change of rule-based reasoning and language. This may be taken to suggest that by this age rule-based reasoning levels off and principle-based thought become versatile enough to allow swift use of principles underlying language use (Demetriou et al., 2013, 2014). Overall, these patterns suggested that change in different process comes in a wave-like fashion (Siegler, 2006). That is, simpler strategies and concepts may co-exist with their more advanced successors for some time, until the first fade out and the later eventually dominate as underlying relations are explicitly abstracted, aligned, and metarepresented by the AACog core. Finally, it is notable that different indexes of change may highlight different forms of development.

In concern to structure, a powerful general factor was found, which was strongly associated with all processes at all age phases. Three versions of the general factor were examined. The first was related to all measures. The second was primarily representational, only related to reasoning, language, and cognizance. The third was a cascade structure varying in composition with time. Below we first discuss the implications of these findings for the common core discussed in the introduction. In the section following we focus on development, elaborating on the relations between this common core with the various executive processes at each of the three phases studied. We also elaborate on the possible relations between our findings and current research on brain development.

4.1. Mapping the mind's core

The factor standing for the common core was very powerful at all age phases, running highly through all of the inferential (>0.8), language (>0.9), and awareness processes (>0.6). In fact, every one of the domains involved in these processes was found to stand equally well as a proxy of this common core (Fig. 6). Notably, Gustafsson and Undheim (1996) found that the relation between G and Gf is almost unity. This study suggested that this finding was accurate but it goes beyond Gf: It concerns all cognitive and language factors that are complex enough to activate the core for their functioning. Moreover, either taken in itself (Fig. 6B) or via a proxy (Fig. 6), this core is strongly related to executive processes, although these relations varied extensively with age. Therefore, the common core cannot be equated with psychometric g or the mental structures dominating in developmental theories. These classical structures are too dependent on inferential processes, while the core identified here relates, additionally, to processes which are minimally inferential, such as vocabulary. This core cannot be equated with the modern version of fluid intelligence either, which comprises, in addition to inferential processes, various control processes (Blair, 2006; Kyllonen & Christal, 1990). For this to be possible, our common core would have to be dominated by control and working memory, which again was not the case.

As noted in the introduction, AACog is minimally inferential in that it involves abstraction and relational processes allowing search and encoding of similarities or regularities in the environment into representations and concepts. Combinativity and generativity of some sort (including Piagetian reversibility) may be part of this encoding process. For instance, these processes might underlie both the interlinking of propositions in deductive reasoning in search of a true inference and the arrangements of words and sentences to convey meaningful messages in language. However, in itself, AACog is silent about the exact identity of these processes as these may vary across domains or developmental levels. If one would have to specify constraints on its operation, Halford's (Halford et al., 1998) notion of relational complexity may be a good approximation. This reflects limitations in relational processing. Recently, Hansell et al. (2015) showed that relational complexity is highly heritable (67%), it is a major component of genetic covariation between working memory and reasoning, and it genetically overlaps with IQ (0.59). Rules in various domains, including the logical principles of inductive or deductive reasoning (Christoforides et al., 2016), principles underlying hypothesis testing, mathematical computations, etc., must be learned as such. Thus, criteria for acceptable performance may vary across domains (Demetriou et al., 2014). Cognizance is highly important because it directs relational mapping and decision making.

Special mention about the role of language is needed. We found that, although gradually intertwined, reasoning, language, and cognizance are equally good proxies of G. It is most likely that the seeds for thought and language that contributed to the formation of the core identified here co-evolved for a very long period of time, probably starting since the Neanderthals first appeared, about 500,000 years ago (Dediu & Levinson, 2013). Thus, they are so inextricably linked, genetically, brain-wise, ontogenetically, and culturally, that their interactions always go both ways. In combination, these processes allow for the compositionality, recurrence, generativity, and hierarchical integration of mental action sequences engaged by problems asking for understanding and solution. Through the millennia, evolution abstracted this structure from various domains including language and projected it to a level higher than any one of them. Interestingly, Chomsky espoused this view some time ago: “The logical notions are embedded in our deepest nature, in the very form of our language and thought, which is presumably why we can understand some kinds of logical systems quite readily whereas others are inaccessible to us without considerable effort… if at all (1988, p. 99).

The nature of G is disputed ever since Spearman invented it. Interpretations vary between two extremes: On the one hand, the Spearman's (1904) camp postulates that G is a powerful biological (e.g., representational and processing efficiency of the brain) and psychological mechanism (inferential power) that constrains all learning and thinking because the output of any effort depends on what is initially invested in it (Gottfredson, 2002; Jensen, 1998). On the other hand, the interactionist camp (Thomson, 1916) assumes that "There is no psychological process that corresponds to psychometric g" (Kovacs & Conway, 2016, p. 171). For this camp, G is an algebraic consequence of the interaction (van der Maas et al., 2006) or the sharing of some common process, such as executive control (Kovacs & Conway, 2016, p. 171), of various specific processes as they are jointly brought to bear on different problems.

The present study suggests a middle ground interpretation. In line with the first camp, we do ascribe psychological substance to G. Specifically, G is considered as a kind of dynamic field where different specialized processes, such as deductive and inductive inference, quantitative estimation, hypothesis testing, mental rotation, etc., operate. Abstraction defines what commonalities between elements of information the mind can see, if any; alignment defines the mapping possibilities the mind has; cognizance defines how the mind takes stock of previous related encounters, ensuring some initial direction. The state of these processes defines the possibilities available to a given individual at a given time, because rules in different domains must be learned as such. Therefore, these processes may be a cause of both developmental differences and individual differences. Thus, in line with the interactionist camp, we do assume that G may express itself differently in different domains depending upon the interaction with them. Also, G is reformed with development at various levels, including the nature of representations dominating and the refinement of their manipulation that is possible at each developmental phase. Thus, we turn to development.

4.2. Relations between processes across developmental cycles

Despite differences in descriptions, the cycles outlined in the introduction have been identified by all developmental theorists (e.g., Case, 1985; Fischer, 1980; Pascual-Leone, 1970; Piaget, 1970), suggesting a powerful developmental phenomenon to be explicated. It was anticipated that relations between the central core and age would vary to reflect changes in the operation of its constituent processes and their relations. It was indeed found that different executive processes reached maturity at different ages and their relations with the central core did vary with age. Thus, the relative importance of each as a contributor to the development of reasoning varied with development. In the 9–11 years phase, AACog related primarily to attention control and shifting. Therefore, improvements in these processes facilitate search of conceptual spaces and abstraction of their underlying rules. This is expressed in the conceptual fluency executive program of this phase. However, self-evaluation is not yet very accurate. In line with this interpretation, there is recent research suggesting that development of working memory in childhood draws extensively on the development of attention control (Cowan, 2016). Notably, the establishment of this conceptual fluency executive program coincides with changes in the brain which relate to executive control, such as the anterior cingulate and associative networks in the inter-parietal cortex (Demetriou et al., 2016).

In the 11–13 years phase these relations are still present, because executive control still improves but cognizance also becomes sharper. Obviously, in this phase, command shifts to relations between underlying rules connecting mental spaces that may result in the construction of principles. This leads to strategies allowing direct control of representational spaces. Improvement of self-evaluation in this phase reflects the emergence of general validity and truth criteria that may be called upon in judging mental outputs relative to goals. In this phase, attention control-shifting networks are still under formation in the brain but higher level networks related to deductive reasoning and second-order relations also emerge. Specifically, in this phase, left and right dorsolateral and dorsomedial prefrontal cortex connections are established (Wendelken, Ferrer, Whitaker, & Bunge, 2015).

These networks completely dominate in the 13–15 years phase. In this phase variability relates primarily to representational and cognizance processes. It is notable that, in this phase, cognizance becomes increasingly accurate and cohesive as indicated by the relation between the cognizance factors. In this phase, several long distance paths are established in the brain. These involve connections between the left rostro-lateral prefrontal cortex and the inter-parietal lobule. Also, connections between prefrontal hubs and the cerebellum are established, carrying fine tuning and error detection, spotting network inconsistencies These patterns align well with the assumption put forward in the introduction that the inferential relevance mastery program dominating in this phase integrates the mental flexibility of the previous cycle into an evaluation system yielding evaluations of the relations between mental spaces vis-à-vis various types of standards. These may be applied to evaluate relations for truth, consistency, accuracy, esthetics, etc. These changes are consistent with research showing that development of self-reflection and conscious awareness drive children's ability to control their thoughts and actions. (Lyons & Zelazo, 2011).

In conclusion, intelligence expresses itself differently at successive developmental phases. In the first of the phases investigated here, individuals still strive to stay on focus and steer their mental functioning according to plans. As a result, the core of intelligence in this phase appears primarily dependent on attention and shifting. In the phase following, with attention and shifting rather well mastered, the core shifts to inferential-representational processes: Naturally then at this phase individuals should master the rules underlying these processes. In the phase following, individuals master awareness-symbolic processes. Therefore, representations in each next cycle impose different demands and constraints on the three AACog processes. This course of development has a performance cost. The number of candidate responses increases at each next developmental phase, making choices and response assembly increasingly harder (Carey, Zaitchik, & Bascandziev, 2015).

Thus this model offers an answer to an important but never satisfactorily answered developmental question: Why are later levels of intellectual development more difficult to attain than earlier levels? The present findings suggest that implementing the three processes involved in AACog (i.e., abstraction, alignment, and reflection and metarepresentation) becomes increasingly difficult across the cycles because the degrees of freedom increase exponentially across cycles, rendering mistakes more likely. Also, reflection and metarepresentation may be increasingly difficult to perform because each next cycle's representations are more difficult to visualize by the mind's eye (i.e., episodes, their mental analogues, rules, and principles). These very reasons may explain developmental and individual differences across domains. That is, the transcription of AACog into different thought domains may vary according to both phase-specific and domain-relevant constraints and processing peculiarities. These reflect the representational character of the phase concerned and the relational character of the domain. For example, a domain that is heavily based on relations between principles and an unfamiliar representational system, such as advanced mathematics, is more difficult to implement available AACog possibilities than a domain based rules and a familiar representational system, such as categorical reasoning.

4.3. Implications and limitations

These findings have important theoretical, methodological, and practical implications. Hopefully, we showed above that this study contributes to the resolution of some long-standing disputes in psychology, such as the nature of G or the increasing variability between individuals along developmental phases. Concerning method, the models tested here suggested that modeling processes over a wide range of developmental phases yields a picture of relations that is drastically different from their picture revealed when focusing on specific developmental phases. Researchers must be aware of these differences because they suggest that phase-sensitive tests are needed to capture different profiles and phase-sensitive interventions must be designed if they would be optimally efficient. Also, these findings bear important implications both for learning and diagnosis of individual differences.

Any study is limited. We see five limitations in this study that would have to be removed by further research. First, although technically sufficient, the sample size was rather limited. Larger samples in each age group would strengthen confidence to the power of our findings. The second limitation is the cross-sectional character of this study. Therefore, the present findings would have to be validated by longitudinal evidence mapping change in the same individuals rather than differences between age groups. It is well known that these differences may well reflect factors that are not developmental. The third limitation comes from the rather limited developmental span covered by this study. Further research would have to investigate other developmental phases as well, because in other phases cognitive profiles may differ from those found here. Fourth, research would have to cover other aspects of the processes involved here. For example, studying awareness of mental processes as such rather than the evaluation of their output may show that cognizance operates differently than found here.

Finally, brain research would have to investigate how processes in AACog map onto brain processes. For instance, it would be important to test the assumption that abstraction, alignment, and cognizance are served by different brain rhythms, such as alpha, beta, gamma, and theta rhythms (Buzsaki & Brendon, 2012). Also, it is important to examine if developmental changes in the relations between brain rhythms couple with the changes in the relations between processes according to the phases specified here. Research in our laboratory is moving in these directions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.intell.2017.01.006.

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