Intelligence 90 (2022) 101602

Contents lists available at ScienceDirect

Intelligence

journal homepage: www.elsevier.com/locate/intell

Changing developmental priorities between executive functions, working memory, and reasoning in the formation of g from 6 to 12 years

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A R T I C L E I N F O

Keywords:
General intelligence
Ability differentiation
Developmental differentiation
Attention control
Working memory
Reasoning

A B S T R A C T

General intelligence, g, is empirically well established, although its psychological nature is debated. Reductionists ascribe individual differences in g to basic processes, such as attention control and working memory. Interactionists strip g of any psychological process, postulating that it is an index of interactions between processes. Here we postulate that the cognitive profile of g varies at successive developmental phases according to the understanding priorities of each phase. This study combines a large cross-sectional sample of children from 6 to 12 years ($N = 381$) with a longitudinal sample tested twice ($N = 109$) to examine changes in the relations between attention control, working memory, and reasoning. A combination of structural equation modeling, differentiation modeling, and latent transition modeling demonstrated that g does change in development; at 6–8 years, g was primarily dominated by changes in attention control; at 9–12 years it was primarily dominated by changes in working memory. Developmental transitions in reasoning levels were driven by the process dominating in each phase. A theory is proposed integrating psychometric and developmental models of intelligence into a comprehensive system. A strong assumption of the theory is an ever-present central meaning-making core, noetron, involving Alignment, Abstraction, and Cognizance processes, is systematically transformed with age in differing developmental phenotypes.

1. Introduction

This study explored how general cognitive ability, g, is formed in development, from 6 to 12 years. There is general agreement that g is empirically robust, reflecting the positive manifold, the fact that cognitive tasks are positively correlated (Jensen, 1998; Spearman, 1927). In the currently dominant Cattell-Horn-Carroll Hierarchical model of intelligence (CHC), g resides at the apex of several broad factors: fluid intelligence (gf, inductive, deductive, and analogical reasoning); crystallized intelligence (gc, knowledge in different domains); mental efficiency (e.g., processing speed, attention control, and working memory); problem solving in various domains (e.g., quantitative, verbal, and visual-spatial domain) (Carroll, 1993; McGrew, 2009; Schneider & McGrew, 2012). There is also general agreement that, although always present (e.g., Demetriou et al., 2017; Yu, McCoach, Gottfried, & Gottfried, 2018), g changes with age (Carroll, 1993; Demetriou et al., 2017; Jensen, 1998; Spearman, 1927). However, the nature of g and its possible changes are still disputed (Breit, Brunner, & Preckel, 2020; Breit, Brunner, & Preckel, 2021; Molenaar, Dolan, Wicherts, & van der Maas, 2010; Tucker-Drob, 2009), it is accepted that it reflects the state of mental processes in the individual and possible differences between individuals in these processes rather than characteristics of the tasks used to address mental processes. This state may be specified at several levels, genomic (von Stumm and Plomin, 2021), brain, (Protzko & Colom, 2021; Haier, 2016), and behavioral (Jensen, 1998). Below we outline theories about the nature of g, discuss research on its change with age, and derive predictions from these theories to be tested by this study.

1.1. *The nature of g*

Spearman (1927) defined g in terms of three laws: (1) apprehension of experience, the mind becoming aware of its own experience (p. 243); (2) eduction of relations, grasp of a commonality between two or more

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https://doi.org/10.1016/j.intell.2021.101602
Received 10 August 2021; Received in revised form 9 November 2021; Accepted 9 November 2021

elements; (3) and eduction of correlates, projection of a relation between two elements to other pairs of elements (Jensen, 1998; Spearman, 1927). Spearman studied the eduction mechanisms extensively and suggested that they equally define g. He also hypothesized that the quality of these mechanisms and individual differences in using them reflect mental energy, brain's efficiency in representing and processing information. Spearman suggested that apprehension of experience relates with mental clearness of representations needed by the eduction mechanisms to carry out abstractions, but he admitted that it "remains an unknown continent for future explorers" (Spearman, 1927, p. 243). For about a century (see Carroll, 1993; Jensen, 1998), research followed Spearman's lead, studying the eduction mechanisms and their relations with aspects of processing efficiency, such as processing speed (e.g., Jensen, 2006; Sheppard & Vernon, 2008), attention control (e.g., Blair, 2006; Schubert et al., 2021Schneider & McGrew, 2012), and working memory (e.g., Gignac & Weiss, 2015; Kane & Engle, 2002; Kyllonen & Christal, 1990). This research showed that all aspects of processing efficiency are related to g, but g cannot be reduced to any of them because the variance accounted for by each (between ~5 and 25%) is rather low (Demetriou, Makris, Kazi, Spanoudis, & Shayer, 2018). The only one of the broad factors found to be almost identical with g was gf (Gustafsson, 1984; Gustafsson & Undheim, 1996), implying a return to Spearman's initial definition of g.

In response to this state of affairs, interactivist theories questioned the assumption that g reflects any psychological process as such. One of these theories, mutualism, claimed that intelligence emerges from the *mutual interactions* between processes, such as executive function, working memory, and reasoning; g is an index of the *relations* between processes rather than of any process as such. It is recognized that some processes may occupy a more central position in a network of interactions because they relate with more processes than others, pulling interactions in their direction (van der Maas et al., 2006, van der Maas et al., 2017). Recently, Process Overlap Theory (POT), drawing on this assumption, ascribed a privileged role to executive function, assuming that it is used by domain-specific processes, setting a ceiling which masks individual differences in different domains (Conway et al., 2005; Conway & Kovacs, 2018; Kovacs & Conway, 2016). Interactivist theories also postulate that interaction as such is a developmental force because change in one process may influence other processes.

Interactivist theories are criticized on technical and psychological grounds. Technically, it is mathematically possible to abstract hierarchical structure and thus g from networks modeling interactions (Golino et al., 2020). Psychologically, these theories lack a meaning-making mechanism: executive functions such as speed, attention, or working memory may enable mental representation and processing but they do not generate meaning. Therefore, a mechanism is needed linking the environment with the organism, interpreting encounters, and generating behavior of value to the organism (Demetriou, Spanoudis, Makris, Golino, & Kazi, 2021).

Recent research suggests that relational integration is the basic mechanism of understanding underlying g. It comprises (1) mapping perceived stimuli with represented relations (Jastrzębski, Ociepka, & Chuderki, 2020); (2) mapping inferred relations (e.g., larger than) with relevant relations stored in memory (e.g., horse > dog > mouse) (Hannon & Daneman, 2014); (3) reducing different stimuli into new representations (Dauvier, Bailleux, & Perret, 2014; Oberauer, Sűß, & Wilhelm, & Wittman, 2008). Consciousness (Dehaene, Lau, & Kouider, 2017) and awareness of mental processes, often called metacognition (Flavell, Green, & Flavell, 1990), or awareness of mental states, often called Theory of Mind (Demetriou, Makris, Kazi, Spanoudis, & Shayer, 2018; Wellman, 2014), are also considered important for meaning making. These processes enable subject-level experience ascribing intrinsic values to mental states (Cleeremans & Tallon-Baudry, 2021); in turn, these enable value-based choices and mental-self regulation based on subjectively meaningful experience (Demetriou, Golino, Spanoudis, & Makris, 2021). Notably, recent evidence showed that Theory of Mind relates with psychometric g (Coyle et al., 2018).

Integrating over this research, Demetriou, Makris, Kazi, Spanoudis, & Shayer (2018, Demetriou et al., 2018, Demetriou, Spanoudis, et al., 2021) suggested that the core meaning-making mechanism underlying g involves the following processes: (i) Alignment, a search, vary, and align process mapping stimuli and representations onto each other according to goals; (ii) Abstraction, identifying invariant characteristics across stimuli or representations that may satisfy the goals (Burgoon, Henderson, & Markman, 2013); (iii) Cognizance, monitoring alignment and abstraction processes, revisiting their operation, objects, and products, and metarepresenting them together with value-tags for future use, based on successes and failures (Demetriou et al., 2013; Demetriou, Makris, Kazi, Spanoudis, & Shayer, 2018). These processes operate together as an integral mechanism, the AACog mechanism, called "*noetron*", after nous, the Greek term for mind, to stress that it is the mind's basic noetic mechanism. Its brain analogue comprises a network of regions physically implementing the mental processes above (Demetriou, Golino, et al., 2021; Spanoudis & Demetriou, 2020).

1.2. Change in g

There are two aspects of change in g which are not explicitly distinguished in the literature: (i) change in the *cognitive composition* of g with growth; (ii) change in the relations between g and specific cognitive processes resulting from an interaction between increasing g and learning. Traditionally, the first aspect is studied by developmental research. The second is concerned with possible individual differences in how individuals with different levels of g use available cognitive ability to master different concepts or skills. Differences in language and methods between developmental and psychometric research obscure understanding. Explicit specification and integration of constructs is needed for progress in understanding intelligence.

Change in the cognitive nature of g. Spearman recognized that "*g* increases from birth-at first rapidly, then more and more slowly-until somewhere not later than 15-16 years" (1927, p. 375). Increasing clearness of mental content due to apprehension of experience is a major factor in this increase. Developmental change of cognitive ability is the focus of developmental research. Piaget (2001) explicitly stated that his stages of reasoning development are forms of Spearman's g coming with age. Indeed, recent research suggests that performance on psychometric and Piagetian tasks are highly related, loading on a common g factor (Rindermann & Ackermann, 2020). Notably, the CHC model includes reasoning on Piagetian tasks as part of gf (Carroll, 1993). In Piagetian theory, changes in understanding (i.e., assimilation), rendering intellect increasingly predictive and thus less error-prone, is driven by reflective abstraction; this explores and refines relations between representations, rendering them increasingly inclusive, abstract, and precise (Piaget, 2001). Piaget's reflective abstraction and Spearman's apprehension of experience converge in causing progressive clarification of representations and integration of inferential mechanisms. Karmiloff-Smith's (1992, 1994) Representational Redescription (RR) restates these mechanisms in modern cognitive science terms: RR is a "process by which information that is *in* a cognitive system becomes progressively explicit knowledge *to* that system" (p. 693). RR enables conscious access to and systematic inter-relation of representations, causing increasing "explicitation" and modularization of mental processes.

Demetriou and colleagues (Demetriou et al., 2017; Demetriou, Golino, et al., 2021; Demetriou, Makris, Kazi, Spanoudis, & Shayer, 2018) suggested that changes in g are reflected in changes in the three aspects of noetron, which enhance the scope of concepts that may be constructed: 1) type of representations that may be aligned; 2) relations between representations that may be abstracted; 3) levels of awareness allowing choice and modification of representations and relations. With growth, episodic representations are replaced by reality-based mental signifiers, subsequently linked to generic symbols. Perception-based alignments and abstractions of similarities are replaced by integration of realistic mental representations, subsequently replaced by rule-based and principle-based relations. Awareness shifts from perception-based characteristics of representations to underlying relational processes (Demetriou, Makris, Kazi, Spanoudis, & Shayer, 2018). These changes alter developmental priorities. When a process is highly demanded for efficient functioning, this process and g integrate increasingly up to a critical integration point satisfying functional demands; after this point the two may dissociate, as the formation of g shifts to other priorities (Demetriou et al., 2017; Demetriou & Spanoudis, 2018).

In infancy, noetron handles perceptual experiences and interactive episodes; relational integration is based on Bayesian statistical inference which capitalizes on perceptual regularities and behavioral successes (Piantadosi, Tenenbaum, & Goodman, 2016). With the representational explosion indexed by language at 2 years, episodic representations are embedded into realistic mental representations that may be used to guide action. Thus, attention control and awareness of the perceptual origins of representations become major priorities from 2 to 6 years. Mastering these processes allows preschoolers to organize activity according to representations rather than simply responding to current experiences; it also enables understanding behavior of other persons. Inference is present in this phase, but the relations between representations are read out from the experiential structures from which they emerged (Demetriou, Makris, Kazi, Spanoudis, Shayer, & Kazali, 2018; Ricco, 2010). Hence, attention control and representational awareness but not inference mark g from 4 to 6 years (Demetriou et al., 2017; Demetriou, Golino, et al., 2021; Demetriou, Spanoudis, et al., 2021; Kazi, Kazali, Makris, Spanoudis, & Demetriou, 2019; Spanoudis, Demetriou, Kazi, Giorgala, & Zenonos, 2015).

With attention control and representational awareness established, priorities change at 6–8 years. Relations between representations as such must be worked out. Cognitive priorities are redirected from linking representations with the environment to inter-relating representations. Induction of rules connecting representations emerges at 6–8 years and it becomes increasingly dominant from 8 to 12 years. Thus, inductive inference, inferential awareness, and working memory mark g from 8 to 11 years. At 12–13 years, these processes are crystalized in logical principles underlying rule-systems. In adolescence, deductive reasoning and awareness of logical constraints mark g (Demetriou et al., 2017; Makris, Tahmatzidis, Demetriou, & Spanoudis, 2017). In short, noetron involves different forms of representations, uses different forms of reasoning in sake of relational integration, and draws on different forms of awareness to guide relational integration.

Change in the relations of g with specific processes. In psychometric research, this type of change is known as ability differentiation; it is based on Spearman's (1927) Law of Diminishing Returns (SLODR). SLODR postulates that the relation between g and performance in different domains decreases with increasing g: investment of high available ability in domains of interest would cause higher variation between these and other domains compared to investment of low available ability, because high ability would make chosen domains much better than other domains. The developmental aspect of SLODR is developmental differentiation: with development, specific abilities differentiate from g because g increases with age (Garrett, 1946). In short, the concern here is not how g changes but how it is used.

Theoretical predictions and the state of the art. Lack of clarity in conceptualizing change by different theories causes conflicting predictions. Classic psychometric theory and some modern versions of it predict both ability and age differentiation. Detterman's (1987) system's theory and POT (Kovacs & Conway, 2016) align, predicting increasing differentiation: these theories assume that if a key process, such as executive function, is handicapped, it sets a low ceiling for all processes using it, causing homogeneity of performance. Interestingly, the RR model, (Karmiloff-Smith, 1992, 1994), although developmental, also predicts differentiation, for the opposite reason: increasing explicitation caused by redescription of representations results into increasing modularization, implying differentiation.

Developmental theory predicts that the relation between reasoning and performance in different domains increases with reasoning development. For instance, Piagetian theory recognizes that there may be a decalage of performance across domains in concrete thought because mental operations are not completely integrated into a reversible structure. Decalage between domains disappears when formal thought is attained because complete reversibility allows overcoming possible contextual differences between domains. In short, increasing integration of reasoning processes results into increasing unification of mental processes across reasoning domains (Piaget, 1970, 2001). Neo-Piagetian theory associated reasoning development with increasing processing efficiency reflected by processing speed (Case, 1985; Kail, Lervag, & Hulme, 2015; Kail & Miller, 2006), executive control (Diamond, 2013; Zelazo, 2015), and working memory (Case, 1985; Halford, Wilson, & Phillips, 1998; Pascual-Leone, 1970; Pascual-Leone & Johnson, 2021). Mutualism, an interactivist model, also predicts integration because interactions strengthen relations between processes (van der Maas et al., 2006, van der Maas et al., 2017).

The developmental priority theory departs from the predictions above in two respects. First, it suggests that changes in the relations between g and specific processes when g is under formation, from birth to early adulthood, is different from changes in the relations between g and functioning in different domains after g is consolidated in adolescence. In the first case studied here, these relations vary according to developmental priorities. For instance, in childhood, attention control gradually dissociates from g and reasoning and working memory integrate with g, reflecting shifting of priorities from using representations to commanding their integration. In the second case, solely measuring g is not enough to specify SLODR; additionally, the effort invested across different domains must be measured to specify ability differentiation. Obviously, learning differences across domains may cause variation of performance across them, both within and across individuals; however, this variation reflects differences in the implementation of g rather than differences in the processes involved in g. Therefore, developmental changes in the process profile of g with advancing age are not the same with changes in the facility of using mental processes at a given age due to differences in learning invested in different domains.

Empirical findings are inconsistent. In a recent excellent review of 23 studies, Breit, Brunner, and Preckel (2021) noted that 16 studies found no evidence of developmental differentiation. Some studies found some differentiation in some processes, reflected in some measures, such as the decrease of the variance accounted for by g, which decreased from 41.3% at 3 years to 22.8% at 9 years of age (Quereshi, 1967). Others found that differentiation interacts with age and ability. For instance, Facon (2004) did not observe higher homogeneity of performance in low IQ children from 4 to 9 years compared to their high IQ agemates. However, he did observe that homogeneity of performance in low IQ individuals increases in adolescence (Facon, 2006). In their own study, Breit et al. (2020) found that differentiation may be specific to some abilities in the period from 5 to 12 years: there was (weak) evidence for differentiation in numerical reasoning but no evidence for differentiation in figural and verbal reasoning; also, there was no interaction between ability differentiation and developmental differentiation during childhood. Along this line, Hartung, Engelhardt, Thibodeaux, Harden, and Tucker-Drob (2020) found that inhibition differentiates from other executive functions from 10 to 15 years but working memory and updating preserve a uniform pattern of relations with age and other executive processes from 7 through 15. However, Breit, Scherrer, and Preckel (2021) did not find any differentiation of various intellectual processes from 12 to 15 years.

Obviously, differentiation is hard to demonstrate but this is due to conceptual and methodological limitations. The developmental priority model suggests that relations between g and specific processes vary as a function of the process measured and the age period sampled. The same process may relate differently with g in different age periods and different processes may relate differently with g in the same period.

Thus, finding differentiation requires measuring the required combination of processes over an age period in which the phenomenon may occur. Technically speaking, none of the studies summarized above (most reviewed in Breit, Brunner, & Preckel, 2021) satisfies this criterion. Also, studies reporting no differentiation of specific processes, such as working memory (Gignac & Weiss, 2015), or broad abilities, such as crystalized and fluid intelligence (Hartung, Doebler, Schroeders, & Wilhelm, 2018), in adulthood are not related to the present concerns requiring that possible differentiation is examined in age periods in which g is under formation.

This study satisfies this requirement, measuring attention control, working memory, and reasoning from 6 to 12 years. All abilities develop in this period, although slopes of change differ, reflecting differences in the time they reach their steady state (prediction #1); as a result of these differences, processes integrate with g in phases of accelerated development, and differentiate from it when approaching their steady state. For instance, attention control would integrate with g early in age and differentiate from it later; reasoning and working memory would integrate with g at a next phase and differentiate even later (prediction #2); Fig. 1 illustrates changes in patterns of integration and differentiation with changes in age and g. Also, developmental causality would reflect developmental priorities, so that changes in attention control cause changes in working memory and changes in working memory cause changes in reasoning (prediction #3). These predictions are to be contrasted with wholesale predictions of differentiation (psychometric, POT, and RR theory) and wholesale predictions of integration (developmental theory and mutualism).

2. Method

2.1. Participants

Two samples of children were involved, the longitudinal and the extended sample. In the longitudinal sample, at first testing, 109 children were tested. These participants were sampled randomly among first to fifth primary school grade and gender as part of another experiment (Demetriou, Mouyi, & Spanoudis, 2008). From first through fifth grade, there were 23 (11 female; mean age 6.69 years, SD = 0.32), 21 (12 female; mean age 7.73 years, SD = 0.30), 20 (10 female, mean age 8.89 years, SD = 0.49), 20 (10 female; mean age 9.80 years, SD = 0.26), and 25 children (13 female; mean age 10.69 years, SD = 0.26), respectively. These children were examined at second testing, one year later, together with all other children in the school, as part of the extended sample (*N* = 381). From first through sixth grade, children in the extended sample were as follows: 61 (32 female; mean age 6.69 years, SD = 0.24), 61 (28 female; mean age 7.69 years, SD = 0.32), 69 (36 female; mean age 8.77 years, SD = 0.30), 66 (24 female; mean age 9.71 months, SD = 0.40), 53 children (24 female; mean age 10.73 months, SD = 0.32), and 71 children, respectively (36 female; mean age 11.71 months, SD = 0.32). These children come from middle class families living in Nicosia, the capital of Cyprus. Greek was the native language of all children.

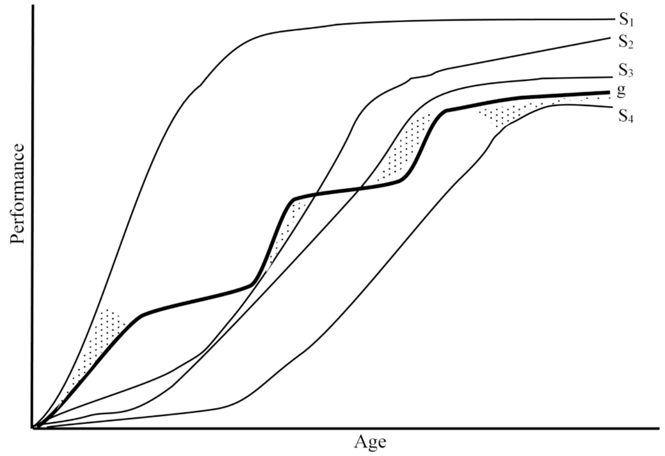


Fig. 1. Shifting relations between g and specific processes (S_i) as a function of functional priorities of successive developmental phases.
Note: Shaded areas indicate regions of strengthened relations between g and a specific process.

2.2. Tasks

2.2.1. Design

Children were examined by a large battery of tasks (Demetriou et al., 2008) addressing attention control, working memory, and reasoning. Tasks varied in complexity to address processes gradually mastered in the age period involved. These tasks are summarized in Table 1 and fully presented in Supplementary Material.

Attention control. Attention control tasks addressed four levels of complexity, based on the number of stimuli, presence, and nature of interference (Demetriou et al., 2008; Jensen, 1998, 2006; Spanoudis et al., 2015).

Attention focus (AF). The Simon task, the simpler of the tasks used, addressed attention focus. This task required identifying where in one of two locations a stimulus appeared (left or right side of the screes). RT is longer when the response side is spatially incongruent with the stimulus position (left vs. right and vice versa) as compared to trials where the stimulus and response side coincide. The Simon effect captures efficient perceptual focus and suppression of the prepotent tendency to respond to the stimulus position (Zhang, Zhang, & Kornblum, 1999).

Perceptual discrimination (PD). These tasks required discriminating which of two familiar stimuli was bigger; two pictures, one small and one big, were presented simultaneously on screen, one on the left and the other on the right half of the screen. Participants chose the bigger of the two. Objects in each pair related physically (e.g., leaf vs. tree), functionally (e.g., hammer vs. nail), and conceptually (e.g., apple vs. cherry).

Perceptual control (PC). Several Stroop-like tasks addressed perceptual control, requiring identifying a perceptual aspect of stimuli, such as the ink color in which a word was written or the component figure building a complex figure, controlling for interference of another aspect, such as word meaning or the whole figure, which dominates in the perceptual setup. Verbal, numerical, and figural stimuli were used. In the verbal task children named the ink color of color names denoting a different color. In the numerical task children recognized the small component digit composing a different large digit (e.g., large 7 composed of small 4 s). In the figural task they recognized a small geometrical figure composing a different large geometrical figure (e.g., a small circle composing a big triangle).

Conceptual control (CC). These tasks required identifying the weaker of two stimuli by retrieving information form memory, controlling interference of a dominant present stimulus: pairs of objects, a small and a big one, were presented on the left and the right half of the screen; their actual size relation was inverted in the task: objects bigger in reality were smaller on screen. Participants chose the object which was bigger in reality but smaller on screen.

Wrong responses were rare: 5.5%, 6.6%, 5%, and 23.6% of responses to attention focusing, perceptual discrimination, perceptual control, and conceptual control tasks, respectively. Cronbach's alpha both for the 11 attention control measures together (0.91) and each type of attention control (all >0.83) was very high in both the extended sample and the first and second testing of the longitudinal sample (all >0.80).

Working memory. Three tasks addressed short-term or working memory: visuo-spatial short-term memory requiring recall of 2 to 7 patterns of geometrical figures. Working memory requiring integration of information according to (1) a specific rule (recall combinations of number digits and their printing color) and (2) the same rule together with an operation: count dots to specify amount of sets and recall

Table 1
Tasks addressed to different processes according to level of difficulty or complexity.

	Difficulty/complexity levels		
Process	Level 1	Level 2	Level 3
Attention control Rel. = 0.91	Perceptual focus: choosing one of two locations (0.93). Perceptual discrimination: choosing one of two objects (0.91).	Perceptual control: Stroop-like control of perceptual interference (0.87).	Conceptual control: Stimulus to be responded to retrieved from memory, controlling for perceptual interference (0.83).
STSS/WM Reliability, all three: 0.50 Two WM tasks: 0.63	Recall of visual patterns of geometrical figures (2–7 figures)	Storing combinations of number digits and their print color and recall according to a probe indicating the set to be recalled (2 to 7 digits).	Same as in level 2 but numbers presented as sets of dots to be counted, requiring an operation during storage (2 to 7 counting results).
Reasoning (Rel: 0.84)			
Inductive (Rel: 0.64)			
Verbal: Pi, Yi and Xi are all Chinese. Pi likes rice. Yi likes rice. Xi likes rice.	Andreas is not Chinese; Does he like rice?	Li doesn't like rice. Is Li a Chinese?	Can one be a Chinese and not like rice?
Numerical: identify relations between even and odd numbers.	If you put two even numbers together, will they have a left over?	Two numbers are put together and have a left over. Are they odd or even?	A number is impossible to write as a sum of two prime numbers. Can it an even number?
Spatial: identify the rule governing movement in an m × n matrix and predict how one would move in a similar field.	5 × 5 matrices One turn	7 × 7 matrices One turn	11 × 11 matrices Two turns
Analogical (Rel: 0.68)			
Verbal: Identify the missing word in "a to b is like c to d" analogies.	car to street is like ship to? (sailors, anchor, trip, sea).	speech to? (silence, tongue, audience, peace) is like water to fire.	leaf is to (forest, tree, branch, garden) like page is to book.
Quantitative: Identify the relation between number pairs to specify missing number in last pair (double, triple, cubic, double +1, half - 1, square – 1.	1 to 3; 3 to 9; 5 to 15; 4 to?	2 to 5; 4 to 9; 5 to 11; 6 to?	16 to 7; 20 to 9; 8 to 3; 10 to?
Figural/spatial: Raven-like matrices of increasing complexity according to number of dimensions and transformations.	Relation between color (two levels) and shape (two shapes).	Relation between color (2 levels) and shape (2 levels), transformed into a more complex figure according to the one of the shapes above.	Relation between color (2 levels) and shape (3 levels), transformed into a more complex figure according to 2 or 3 of the shapes and colors above.
Deductive (Rel: 0.65)			
Verbal: syllogisms about an imaginary world stated as two premises and conclusion to be evaluated as right, wrong, or undecidable.	Modus ponens: Zan live on the yellow planet and have a triangular head. Four (a Zan) lives on the yellow planet/: Four has a triangular head.	Modus tollens: Zan live on the green planet and have a triangular head. Six (a Zan) does not have a triangular head/: Six does not live on the green planet.	Affirming the consequent: Zan live on the green planet and have a triangular head; Four (a Zan) has a square head/: Four lives on the yellow planet.
Quantitative: place a number (between 0 and 9) in each of four adjacent boxes, based on rules constraining relations between numbers	3-digit problems with 5 rules: 1) third number is 1; 2) if third number is the smallest, the first is 4. 3) there is no 0; second number either the biggest or smallest of all; 5) no number is written twice.	4-digit problems with 6 rules.	4-digit problems with 8 or 9 rules:
Spatial: specify the position of several persons sitting next to each other according to rules constraining how each person is placed in relation to other persons.	Three persons and two propositions (e.g., If Alexis sits next to Demetris, then George will sit next to Stelios).	Four persons and 4 to 6 rules.	Six persons and 4 to or 8 rules.

combinations of number digits and their printing color but. Cronbach's alpha for all three tasks was below optimal (0.52, 0.50, and 0.54 for the extended sample and the two testing waves of the longitudinal sample, respectively); however, it was acceptable when the visuo-spatial task was excluded (0.63, 0.61, and 0.62, respectively).

Reasoning. Tasks addressed inductive, analogical, and deductive reasoning at three levels of difficulty. The first level required to induce or use a specific rule to solve a problem; the second required to combine at least two rules; the third required to explicitly specify rules hierarchically integrated and apply them exhaustively. These levels require early (6–8 years) and late rule-based thought (9–11 years) and early principle-based thought (12–15 years), respectively (Demetriou & Kyriakides, 2006; Demetriou & Spanoudis, 2018).

Verbal inductive reasoning tasks required integrating information about characters in a story and extrapolate to other characters, understanding that inductive rules are always likely. The three levels required increasing grasp of the probabilistic nature of induction. Verbal analogies required abstracting a relation between components of a pair and using it to identify the relation in another pair. The three levels required identifying increasingly abstract relations. Verbal deductive reasoning addressed standard logical relations. The three levels required grasping simple relations (modus ponens), transforming a relation (modus tollens), and embedding a relation into general logical principles (e.g., affirming the consequent or denying the antecedent).

Numerical inductive reasoning tasks required inducing relations between even and odd numbers, given several rules. The three levels required grasp of increasingly abstract rules. Numerical analogies required abstracting the relation between three pairs of numbers to specify the second element of a fourth pair. The three levels required grasp of increasing complex relations, from doubling to counterintuitive relations (e.g., $x^2 - 1$). Mathematical deductive reasoning tasks required specifying relations between numbers according to a set of mathematical rules. The three levels required integrating increasing complex sets of rules to specify relations between numbers.

Spatial inductive reasoning tasks required extracting a rule underlying movement in a spatial arrangement and use it in a similar context. The three levels required abstracting rules in matrices of increasing complexity. Raven-like matrices addressed spatial analogies. The three levels involved increasing numbers of elements and transformations. Spatial deductive reasoning tasks required to specify spatial relations based a set of rules about how elements related to one another, in the fashion of the mathematical deductive reasoning tasks. The three levels required integrating increasingly complex sets of rules to specify the relations between elements.

Cronbach's alpha for the 27 tasks (9 measures for each type of reasoning) was high (0.84 for the extended sample and 0.79 and 0.83 for the two testing waves of the longitudinal sample).

2.2.2. *Procedure*

Testing took place at school in two sessions, on different days. The reasoning battery was administered first followed by the attention control and the working memory tests. The presentation order of tasks was counterbalanced within each session.

The reasoning battery was a paper-and-pencil test. First- and second-grade children completed the test in a step-by-step fashion, following instructions. Tasks were completed one by one, after all children in the classroom completed the current task. Demonstration and explanations were given before taking each task. Older children were given an example and relevant instructions for every type of tasks on the whiteboard, and they proceeded to complete the test on their own, asking for clarifications if needed. Differentiating between the two younger grades aimed to compensate for their lack in testing experience. It would be more costly in accuracy to adopt a uniform approach across age groups because it would be uncertain if lower performance among younger children would reflect lower ability or lack of experience.

All attention control and working memory tasks were examined in the E-prime environment, a computer environment for psychological testing. Each child sat in front of an especially prepared personal computer. All participants were examined by the second author, an experienced schoolteacher. Requirements of each test were explained, and an example was demonstrated before testing. Every task began with a practice session to familiarize children. Children failing this session were excluded.

2.2.3. *Rationale of statistical modeling*

Several statistical methods were used to test our predictions. Results concerning the extended sample are presented first, followed by results for the longitudinal sample. Also, results about developmental patterns are presented before results about relations between processes.

Developmental patterns. To map development, repeated measures Bayesian Analysis of Variance was used, using JASP. Bayesian analysis was preferred because it allows to test hypotheses about expected age and repeated measures effects over the null hypothesis. A separate repeated measures Bayesian Analysis was conducted for each of the three types of processes, namely attention control, working memory, and reasoning. These analyses were conducted separately on the extended sample of 381 children and on the longitudinal sample ($N =$ 109). The combination of analyses of a large cross-sectional sample with the longitudinal sample is a powerful test of possible individual differences and developmental trends. These analyses are summarized here and fully presented in Supplementary Material. Noticeably, comparing attainment at second testing by children of the longitudinal sample with the children of the enhanced sample showed no significant difference on attention control, working memory, and reasoning, indicating no repeated testing effects (all three BFs < 1).

To model transition across levels of reasoning from the first to the second testing of the longitudinal sample, Latent Transition Analysis (LTA) with covariates was employed, using Mplus (Muthen & Asparouhov, 2011; Muthén & Muthén, 1998-2017). LTA specifies patterns of change along performance categories in the variables of interest across testing waves and allows to specify if these patterns are related to other variables of interest. This method is particularly suitable for exploring transitions in 2-wave longitudinal studies.

Relations between processes. To examine relations between processes, various forms of Structural Equation Modeling (SEM) were used. To establish if specialized processes emerge as distinct constructs additionally to g, confirmatory bifactor nested analysis was used, using the EQS program (Bentler, 2006). The various analyses used two scores for attention focusing, three for perceptual discrimination, three for perceptual control, three for conceptual control, three for working memory, and three for reasoning (i.e., inductive, analogical, and deductive reasoning) or three for domains (verbal, quantitative, and spatial) or a mean for each set. Actual reaction times were used for performance on attention control tasks rather than difference scores between tasks addressed to different levels of complexity. Difference scores suffer from low reliability compared to the actual scores involved and they vastly diminish correlations between the tasks involved and other external variables, such as working memory and reasoning used here, thereby jeopardizing the aims of this study (Draheim, Mashburn, Martin, & Engle, 2019; Jensen, 2006, p. 103).

To examine possible changes in the relations between g and the various processes with increasing age, non-linear structural equation modeling was used, using Mplus (Tucker-Drob, 2009). This model, illustrated in Fig. 2, examines how the relations between specific processes and g or age vary at different levels of g or age. A standardized measure of each process is regressed on age and quadratic age to account for linear and quadratic age trends, a common factor standing for *g*, quadratic *g*, the age × *g* product, and the age × quadratic *g* product. Squaring age or *g* maximizes possible growth or ability effects. Thus, it may show if a specific process increases commensurably with age or g at all levels, or of it separates from each after a given level. Quadratic g is the *ability differentiation factor*. Negative relations with a process would imply differentiation of this process from g, as g increases. The *g* × age product is the *developmental differentiation factor;* positive relations would imply that as g increases the processes involved also increase; negative relations would imply that developmental changes in g occur independently of the process concerned. The quadratic g x age interaction shows if relations of specific processes with g vary as developmental level of g: e.g., ability differentiation (negative relation) or integration (positive relation) is stronger for younger individuals.

Evaluating power of samples and methods. To estimate the minimum sample size required to obtain sufficient statistical accuracy for detecting effects of interest in the population power analysis was conducted. Following the method proposed by MacCallum et al. (1996, 2010), which is based on discrepancies between null and alternative RMSEA values, we applied a test of close fit associated with RMSEA values ≤ 0.05. The significance level was $\alpha = 0.05$. The test of close fit indicated that the power of analysis for the total sample ($N = 381$) for the best model involving all relations of interest ($df = 72$) was 0.995. The power

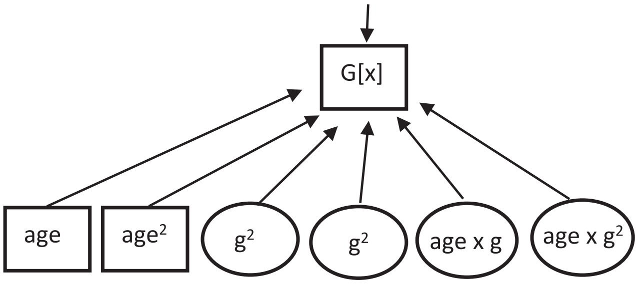


Fig. 2. The general model for testing possible differentiation of mental processes from general intelligence (*g*). Note: Adapted with permission from Breit et al. (2020).

in each group ($N = 190$, df $= 349$) for the two-group models comparing younger (grades 1–3) with older children (grades 4–6) was also very high (0.999). The power for the longitudinal sample ($N = 109$, df $= 349$) was also very high (0.939). Therefore, for approximate power of >80%, null RMSEA = 0, alternative RMSEA = 0.05, and $\alpha = 5\%$, both the total sample and the longitudinal sample would suffice.

Also, we performed a sensitivity power analysis using pwrSEM (Wang & Rhemtulla, 2021) to examine if the longitudinal sample has the power required to give trustworthy relations. This Shiny app is based on a simulation method for estimating statistical power. We tested the power to detect an effect given the population parameter value between manifest variables and latent factors. All population parameters were set to the lowest observed coefficients among variables in line with the existing literature. We estimated the power to detect an effect between the first-order factors standing for the various processes studied and the corresponding manifest variables and between the first order factors and g to approach 1 by setting all factors loadings and covariances at 0.35, and sample size at 110 participants. We also estimated the power to detect an effect when regressing a first-order factor on another. We conducted power analysis with a = 0.05 and the number of simulations set at 1000. Our analysis indicated that all loadings and covariances have power > 0.90; convergence rate was 0.92–1 and 95% of parameter estimates fall within the interval of 0.19–0.7. All loadings in all models fell within this range, implying that the models have the power required to capture relations between processes.

3. Results

3.1. Developmental patterns

Attention control. The best model of the Bayesian analysis applied on attention control tasks showed that performance on all forms of attention control improved throughout the age period studied, although improvement varied across processes ($BF_M = 1.66e + 38$), being minimal in attention focusing which approached ceiling since 3rd grade, whereas perceptual and conceptual control improved in two spurts from 1st to 3rd and from 5th to 6th grade (see Fig. 3; posterior $R^2 = 0.80$).

Performance on working memory tasks also improved across all age years ($BF_M = 140.624$) and the two longitudinal testing waves ($BF_{incl} = 3346.454$) on all three tasks. Performance on the visual-spatial task approached ceiling by 4th grade; performance on the two rule-based working memory tasks improved in spurts from 1st to 3rd, and from 4th to 6th grade (Fig. 3; posterior $R^2 = 0.64$).

Finally, performance improved across all three forms of reasoning throughout the age period examined ($BF_{incl} = 991.066$) and, also, across the two testing waves. $BF_{incl} = 5.026e + 13$ (Fig. 3; $R^2 = 0.59$. There was an interaction with age, indicating that performance in inductive reasoning improved smoothly form 1st through 6th grade; performance in analogical and inductive reasoning improved in spurts from 1st to 3rd and from 4th to 6th grade. Obviously, in this second phase, rule-induction is consolidated causing a spurt in mastering Level 2 in analogical and deductive reasoning.

Table 2 shows the distribution of reasoning levels across age, testing waves, and reasoning forms. Level 1 of all reasoning forms was grasped at first or second grade, indicating that by this age children induce single inductive rules, grasp familiar second-order relations in analogical reasoning, and employ modus ponens in conditional reasoning. Level 2 was attained at 3rd or 4th grade, at 9–10 years, indicating that by this age children induce multiple rules, grasp complex second-order analogical relations requiring some transformations, and reason with modus tollens relations requiring premise transformation. Level 3, requiring explicit awareness of rules and their precise implementation cannot be credited even to sixth grade children as a group; only a minority of them operated at this level at both testing waves.

3.2. Structural changes in development

These developmental patterns justify exploring how development in each process is affected by common mechanisms and mechanisms specific to each. Table 3 shows the correlations and statistics of mean performance on all processes in the extended sample ($N = 381$). An important first step is to establish the operation of specific factors standing for these processes on top of g. In this sake, a series of nested models were tested as shown in Table 4. The first model included only a g factor associated with all scores. At each next test of the model, a factor was added to the factors already in the model, ascending according to presumed complexity, starting from attention focus (see Table 4). Notably, the fit of each next model was significantly better than the previous model, implying that each factor accounted for a significant amount of variance additionally to g. The fit of the final model including all factors was very good, χ^2 (72) = 177.345, $p = .00$, CFI = 0.96, RMSEA = 0.062 (CI = 0.051–0.074), AIC = 33.345. All relations between measures and g or process-specific factors were significant and high (all >0.6).

3.3. The differentiation model

All processes changed systematically from 6 to 12 years, although their form of change varied. These patterns justify using differentiation modeling to explore how the relations between each process and g vary with development. It is reminded that the aspect of differentiation modeled here relates more with changes in the relations between g and specific processes as a function of increasing age rather than as a function of ability differences at a steady state.

The model involved mean performance z scores of each of the four measures of attention control (i.e., attention focus, perceptual discrimination, perceptual control, conceptual control), the three working memory measures (i.e., visuo-spatial WM, WM_{IR}, and 2-rule WM_{EX}), and the three forms of reasoning (i.e., inductive, analogical, and deductive reasoning) or each domain of reasoning (i.e., verbal, mathematical, and spatial). This model was tested on the extended sample twice, first involving the reasoning and second involving the domain scores. In both cases, six models were tested in a stepwise fashion, adding a factor in each next model additionally to the factors included in the previous

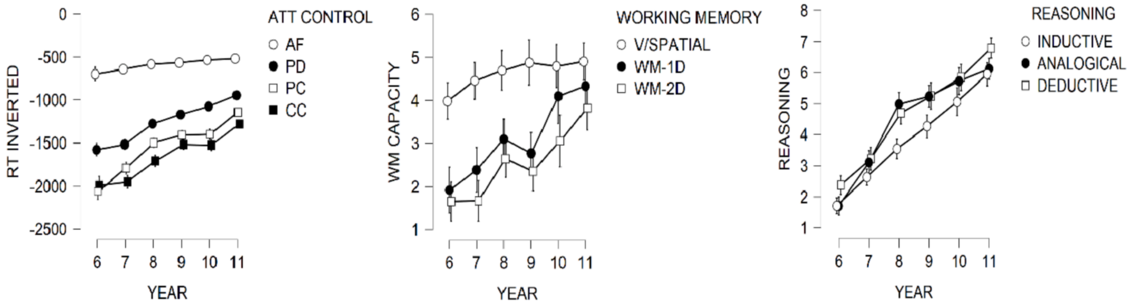


Fig. 3. Performance attained by the extended sample ($N = 381$) on attention control, working memory, and reasoning as a function of age.

Table 2
Percent attainment of reasoning levels as a function of age and testing wave in the longitudinal study (first wave, W1, and second wave, W2) and the enhanced sample (All).

Grade/	Level 1			Level 2			Level 3		
Wave	Induct	Analog	Deduct	Induct	Analog	Deduct	Induct	Analog	Deduct
Grade 1									
W1	60.9	47.8	39.1	8.7	26.1	0.0	0.0	0.0	0.0
All	52.5	37.7	55.7	4.9	8.2	9.8	0.0	0.0	1.6
Grade 2									
W2	73.9	39.1	39.1	4.3	30.4	4.3	0.0	0.0	0.0
W1	61.9	33.3	47.0	9.5	19.0	0.0	0.0	0.0	0.0
All	72.1	23.0	49.2	3.3	50.8	11.5	3.3	0.0	3.3
Grade 3									
W2	57.1	14.3	66.0	14.3	76.2	0.0	4.8	4.8	0.0
W1	55.0	45.5	50.0	20.0	25.0	10.0	0.0	0.0	0.0
All	61.4	17.1	31.4	28.6	68.6	42.9	2.9	7.1	17.1
Grade 4									
W2	70.0	15.0	60.0	25.0	50.0	5.0	0.0	20.0	0.0
W1	50.0	45.0	30.0	20.0	25.0	20.0	0.0	15.0	5.0
All	55.4	18.5	16.9	41.5	67.7	50.8	1.5	10.8	24.6
Grade 5									
W2	55.0	20.0	50.0	35.0	45.0	20.0	5.0	35.0	10.0
W1	36.0	28.0	44.0	44.0	40.0	48.0	16.0	24.0	8.0
All	42.3	9.6	15.4	42.3	57.7	55.8	13.5	26.9	26.9
Grade 6									
W2	36.6	8.0	32.0	36.0	52.0	40.	28.0	32.0	12.0
All	27.8	15.3	19.4	43.1	44.4	31.9	29.2	37.5	48.6

Note: Children were credited with a level if succeeding on two thirds or more of the tasks addressed to each level of each type of reasoning.

Table 3
Correlations, means, and SD between mean scores of all processes.

	1	2	3	4	5	6	7	8	9	10	11
1. Age	1										
2. Perceptual focus	**0.567**	1									
3. Perceptual discrimin	**0.624**	**0.624**	1								
4. Perceptual control	**0.693**	**0.559**	**0.606**	1							
5. Conceptual control	**0.550**	**0.595**	**0.759**	**0.542**	1						
6. Visuo-spatial WM	**0.248**	**0.161**	**0.219**	**0.262**	**0.173**	1					
7. WM_{IR}	**0.270**	**0.202**	*0.113*	**0.280**	**0.141**	**0.159**	1				
8. WM_{EX}	**0.285**	**0.214**	**0.187**	**0.271**	**0.216**	*0.128*	**0.439**	1			
9. Inductive	**0.672**	**0.387**	**0.439**	**0.556**	**0.390**	**0.261**	**0.320**	**0.299**	1		
10. Analogical	**0.634**	**0.440**	**0.455**	**0.583**	**0.377**	**0.311**	**0.322**	**0.301**	**0.584**	1	
11. Deductive	**0.624**	**0.406**	**0.436**	**0.543**	**0.402**	**0.247**	**0.347**	**0.313**	**0.604**	**0.603**	1
Means	9.252	0.592	1.268	1.545	1.664	4.557	3.090	2.570	3.882	4.501	4.719
S.D.	1.751	0.106	0.374	0.413	0.465	1.068	2.891	2.568	2.101	2.321	2.402

Note: Reaction time scores were inverted to vary in the same direction with the rest scores. WM_{IR} and WM_{EX} stand for working memory-integration of representations and working memory memory-executive operation, respectively.
Correlations significant at the 0.05 level are shown in italics (2-tailed). Correlations significant at the 0.01 level are shown in bold (2-tailed).

model. All differentiation factors improved the model fit significantly in the model involving reasoning types (chi-square differences >26 for 10 df, $p < .01$); in the model involving domains, all but the last interactive factor was not significant. Clearly, the patterns of relations between processes, g, and age do change with increasing g and age (see Table 5 and Supplementary Table 2).

Psychometric, POT, and the RR theory predict differentiation of all processes from g; developmental and mutualism theory predict their integration with g; developmental priority theory predicts differentiation of attention control and integration of working memory and reasoning. The results support the prediction of the developmental priority model. All scores related significantly with age, reflecting developmental changes in all processes; negative relations with quadratic age indicated that change with age was not linear (Fig. 3). All processes but visuo-spatial WM related significantly with g. All attention control scores related negatively with both differentiation factors and their interactions. All three reasoning forms and, also, the three reasoning domains related positively with the developmental differentiation factor. These patterns imply that with development reasoning is increasingly integrated with g, becoming stronger at the upper levels of g. Of the three working memory factors, only WM_{IR} related significantly and positively with the developmental differentiation factor.

Fig. 4 shows relations between performance on specific processes with the factor score (extracted from the differentiation model presented above) indicating attainment on the g factor in the three younger and the three older age groups. These figures show how g is formed in each phase. In the first phase, attention control increases with increasing g; this relation vanishes in the second phase. Inversely, in the first phase, increases in g are not related with working memory but they are moderately related with reasoning; in the second phase, the relations with both working memory and reasoning become very strong. Obviously, attention control strongly and reasoning weakly mark g in the first phase; in the second phase, both reasoning and working memory (but not STSS) strongly mark g.

3.4. *Specifying structural relations across developmental phases*

The developmental priority model suggested that relations between individual processes and g change with development, implying that direct interactions between processes also change. A strict test of this

Table 4

Final bifactor nested model and fit statistics of models testing the significance of each process-specific factor.

	G	AF	PD	PC	CC	WM	Gf	R^2
PF1	*0.71*	0.63						0.90
PF2	**0.73**	**0.60**						0.89
PD1	**0.57**		0.45					0.36
PD2	**0.72**		**0.50**					0.60
PD3	**0.72**		0.40					0.80
PC1	**0.76**			*0.19*				0.78
PC2	**0.74**			**0.30**				0.80
PC3	**0.76**			**0.54**				0.73
CC1	**0.65**				*0.52*			0.69
CC2	**0.79**				**0.28**			0.71
CC3	**0.59**				**0.53**			0.63
STSS	**0.28**					0.10		0.09
WM1	**0.28**					**0.78**		0.68
WM2	**0.31**					**0.44**		0.29
IND	**0.61**						*0.48*	0.60
ANA	**0.62**						**0.44**	0.57
DED	**0.61**						**0.51**	0.62
χ^2	1100.176	744.544	573.886	524.919	376.105	324.953	237.827	
df	119	117	114	111	108	105	102	
$\Delta\ \chi^2$		**355.632**	**170.658**	**48.967**	**148.814**	**51.152**	**87.126**	
Δdf		2	3	3	3	3	3	
CFI	0.740	0.834	0.878	0.899	0.929	0.942	0.964	
RMSES	0.148	0.119	0.103	0.099	0.081	0.075	0.059	
AIC	862.18	510.544	345.886	302.919	160.105	114.953	33.827	

Note: This is the final model including all factors used in the differentiation models below. In the process of testing the significance of each individual factor, the first model included only the g factor. At each next run factors were added from left to right according to the columns above. All model differences were significant at the 0.001 level. All factor loadings were significant (in bold). Italicized loadings were fixed to 1 for factor identification.

assumption is showing that the relations between processes vary across phases. That is, during emergence of early rule-based thought, from 6 to 8 years, attention control is the dominant factor influencing working memory and reasoning. During consolidation of rule-based thought, from 9 to 12 years, the influence of attention control on working memory and reasoning diminishes but the influence of working memory on reasoning strengthens.

To test this assumption, a two-group SEM was tested. This model (see Fig. 5) included first-order factors for attention focusing, perceptual control, conceptual control, working memory, inductive, analogical, and deductive reasoning. The following relations between factors were built: perceptual control was regressed on attention focusing; conceptual control was regressed on attention focusing and the residual of the perceptual control factor; working memory was regressed on attention focusing and the residual of perceptual and conceptual control; each of the three reasoning factors was regressed on attention focusing and the residual factors of perceptual control and working memory; also, deductive reasoning was regressed on analogical and inductive reasoning to examine how different types of reasoning inter-relate in each phase. To ensure stability of measurement of factors across the two groups, all measurement-factors relations were constrained to be equal across the two groups.

Three versions of this model were tested. In the first, all relations between factors were constrained to be equal across groups; in the second, these relations were free to vary between groups; in the third, these relations were *constrained to vary in discrete ranges* in each group: in the younger group, the relations between attention control and working memory or reasoning were constrained to vary in a range higher than in the older group; in the older group, these relations were inverted: the relations between attention control and working memory or reasoning were constrained to vary in a range where the higher point was lower than in the younger group; the relations between working memory and reasoning or between analogical inductive reasoning and deductive reasoning were constrained to vary in a range where the lower point was higher than in the younger group. The fit of the constrained model, (χ^2 (368) $= 459.507$, $p = .001$; CFI $= 0.883$; RMSEA $= 0.036$ (CI $=$ 0.024–0.046) was weaker than the fit of the model where relations were free to vary across groups, (χ^2 (358) $= 429.731$, $p = .001$; CFI $= 0.846$; RMSEA $= 0.033$ (CI $=$ 0.019–0.043); $\Delta\chi^2$ (10) $= 29.776$, $p < .001$); notably, the fit of the model where relations were constrained to vary in different ranges (see Fig. 5) was excellent and better than the free model (χ^2 (349) $= 319.565$, $p = .869$; CFI $= 1.000$; RMSEA $= 0.000$ (CI $=$ 0.000–0.015); $\Delta\chi^2$ (9) $= 110.166$, $p = .001$). Clearly, performance in the younger age group was dominated by attention control; in the older group, working memory and reasoning dominated.

3.5. *Modeling developmental transitions longitudinally*

Modeling the cross-sectional sample suggested that there was a shift of importance in the formation of general cognitive ability from attention control to working memory and reasoning. Are these patterns longitudinally present? Three LTA models explored transition from failure to success on the tasks addressed to each of the three levels across the three types of reasoning. In these models, there were two latent categories, performance on the first and performance on the second wave, with two classes in each, failure or success. To explore these transitions, a hierarchical latent class model was employed which involved a higher-order class of “movers” and “stayers” from the one class to the other across the two testing waves (Muthén & Muthén, 1998-2017). In the mover-stayer model, the two classes of the higher-order latent variable identify two types of individuals: (a) the movers, individuals who transition across classes; (b) the stayers, individuals who stay the same class across time. In the class of movers, transition probability is freely estimated using the multinomial logistic regression relationships. In the class of stayers, class-membership (diagonal) probabilities are fixed to 1 and all probabilities indicating class change are fixed at 0, assuming no change from first to second testing (Nylund, 2007).

Two mover-stayer models were tested for each level. In the first model, only performance on the reasoning tasks of the level concerned were involved. In this model, there were two classes, failure and success, in each categorical variable capturing performance at each testing wave; in each of these classes there were two subclasses, movers and stayers. For stayers, the probability of moving to another class across testing

Table 5

Differentiation model (N = 381) tested twice, first including reasoning types (first row of each pair) and second reasoning domains (second row of each pair). Attention control and working memory were included in both.

Process	Age α1	Age^2 α2	g λ1	g^2 Ability diff λ2	Age × g Develop diff λ3	g^2 × age Ability diff & Age diff & Interaction λ4	Intercepts υ	Residual Variance δ^2
Attention								
Perc focus	**0.71 (0.59–0.82)**	**−0.17 (0.26- -0.09)**	0.20 (−0.07–0.4)	**−21 (−0.35- -0.06)**	−0.18 (−0.38–0.03)	−0.16 (−0.31- −0.01)	**0.39 (24–0.54)**	**0.50 (0.41–0.59)**
	0.68 (0.59–0.77)	**−0.14 (−0.22–0.07)**	**0.28 (0.16–0.39)**	**0.11 (−0.19- -0.02)**	**0.21 (−0.32- −0.10)**	**−0.14 (−0.24- −0.04)**	**0.29 (0.19–0.41)**	**0.52 (0.44–0.59)**
Perc Discr	**0.73 (0.63–0.83)**	**−0.12 (−0.20- -0.04)**	**0.34 (0.13–0.55)**	**−0.25 (−0.35- -0.15)**	**−0.41 (−0.59- −0.22)**	**−0.13 (−0.20- −0.06)**	**0.39 (0.28–0.49)**	**0.22 (0.15–0.28)**
	0.71 (0.64–77)	**−09 (−0.14- -0.03)**	**0.44 (0.33–54)**	**−0.16 (−0.22–0.10)**	**−0.45 (−0.52- .−37)**	**−0.12 (−0.15- −0.08)**	**0.30 (0.19–0.41)**	**0.20 (14–0.27)**
Perc Contr	**0.82 (0.74–0.92)**	**−0.18 (−0.26- -0.10)**	**0.19 (0.03–0.35)**	**−0.14 (−0.23- -0.05)**	−0.06 (−0.18–0.07)	**−0.15 (−22- −0.08)**	**0.32 (0.22–0.43)**	**0.42 (0.35–0.48)**
	0.81 (0.73–0.88)	**−0.16 (−0.23- -0.09)**	**0.25 (0.17–0.32)**	**−0.07 (−0.13- -0.01)**	−0.08 (−0.16- −0.003)	**−0.14 (−0.19- −0.09)**	**0.25 (0.14–0.36)**	**0.42 (0.36–48)**
Conc Contr	**0.71 (0.62–0.80)**	−0.10 (−0.18- -0.01)	**0.35 (0.07–0.63)**	**−0.25 (−0.38- -0.12)**	**−0.36 (−0.56- −0.17)**	**−0.18 (−0.26- −0.09)**	**0.36 (0.25–48)**	**0.31 (0.24–0.37)**
	0.69 (0.62–0.76)	−0.06 (−0.13–0.002)	**0.43 (−0.34–0.52)**	**−0.18 (−0.24- -0.11)**	**−0.40 (−0.48- −0.32)**	**−0.17 (−0.23- −0.12)**	**0.29 (0.18–0.41)**	**0.30 (0.24–36)**
Working memory								
WM$_{VS}$	**0.34 (0.20–0.47)**	**−0.16 (−0.27- .-06)**	0.08 (−0.05–0.21)	- 0.05 (−0.18- -0.07)	0.01 (−0.11–0.13)	−0.09 (−0.21–0.02)	**0.22 (0.04–0.40)**	**0.90 (0.70–1.11)**
	0.36 (0.23.48)	**−0.16 (−0.25- − 0.06)**	0.12 (0.002–0.23)	-0.06 (−0.17–0.05)	0.02 (−0.11–0.11)	−0.12 (−0.24–0.000)	**0.24 (0.08–0.39)**	**0.88 (0.67–1.0)**
WM$_{IR}$	**0.31 (0.17–0.44)**	−0.05 (−0.15–0.04)	**0.24 (0.12–0.35)**	0.01 (−0.04–0.06)	**0.23 (0.14–0.32)**	−0.06 (−0.13–0.004)	0.04 (−0.11–19)	**0.82 (0.74–90)**
	0.32 (0.22–0.42)	−0.05 (−0.14–0.04)	**0.20 (0.10–0.30)**	0.01 (−0.08–0.08)	**0.22 (0.13–0.31)**	**−0.08 (−0.15- −0.01)**	0.05 (−0.10–0.19)	**0.84 (0.76–0.91)**
WM$_{EX}$	**0.32 (0.20–0.43)**	0.02 (−0.08–0.04)	**0.22 (0.12–33)**	-0.01 (−0.07–0.04)	0.07 (−0.02–0.16)	−0.06 (−0.12–0.02)	−0.01 (−0.17–0.16)	**0.86 (0.77–0.95)**
	0.32 (0.22–0.42)	0.02 (−0.06–0.11)	**0.20 (0.10–0.30)**	−0.002 (−0.07–0.07)	0.05 (−0.03–0.14)	−0.05 (−0.12–0.01)	−0.02 (−0.17–0.14)	**0.87 (0.79–0.96)**
Inductive	**0.71 (0.57–0.85)**	−0.05 (−0.12–0.02)	**0.27 (0.20–0.35)**	0.04 (−0.07–0.16)	**0.18 (0.06–0.31)**	−0.07 (0.13- −0.01)	−0.00 (−0.18–0.17)	**0.42 (0.36–0.49)**
Analogical	**0.69 (0.56–0.82)**	**−0.26 (−0.34–0.18)**	**0.20 (0.16–0.43)**	−0.05 (−0.09.003)	**0.19 (0.06–0.31)**	−0.07 (−0.13- −0.01	0.30 (0.18.43)	**0.44 (0.36–0.51)**
Deductive	**0.67 (0.54–79)**	−0.08 (−0.16–0.005)	**0.33 (0.20–0.46)**	−0.03 (−0.07–0.01)	**0.18 (0.06–0.31)**	−0.06 (−0.12–0.002)	**0.11 (−0.04–0.25)**	**0.47 (0.40–0.54)**
Verbal	**0.53 (0.46–0.60)**	−0.06 (−0.11–0.004)	**0.23 (0.16–0.29)**	0.00 (−0.05–0.05)	**0.08 (0.02–0.14)**	−0.08 (−0.12- −0.03)	**0.06 (−0.03–0.16)**	**0.36 (0.32–0.41)**
Mathematical	**0.70 (0.65–0.76)**	**−0.14 (−0.19- −0.09)**	**0.25 (0.18–0.31)**	0.04 (−0.04–0.05)	**0.16 (0.11–0.20)**	−0.05 (−0.09- −0.02)	**0.14 (0.04–0.23)**	**0.25 (0.21–0.29)**
Spatial	**0.52 (0.44–0.60)**	**−0.10 (−0.16- −0.03)**	**0.30 (0.22–0.37)**	−0.01 (−0.06–0.04)	**0.15 (0.09–0.15)**	−0.09 (−0.13- −0.04)	0.12 (0.01–0.22)	**0.40 (0.34–0.45)**

Note: The values in this Table are non-standardized model estimates. Mplus does not provide standardized estimates for models involving interactive factors. All factors improved model fit significantly in the model tested on reasoning types; in the model tested on domains all factors improved model fit significantly but the last factor standing for ability differentiation, age differentiation and their interaction (see Supplementary Table 2).

wave was fixed to 0. For movers, it was left free to be estimated. In this model the latent class for first testing was regressed on the higher-order latent stayer-mover class and the latent class for second tasting was regressed on the latent class for first testing. In the second model, four mean change scores (difference of first from second-testing score) standing for change from first to second testing on the attention control tasks and three mean change scores standing for change in the three working memory tasks were included as covariates. In this second model, additionally to the regressions above, the mover class was also regressed on the seven covariates. Comparing the fit of the first model to the fit of the second model would show if and how change in attention control and working memory from first to second testing influences transitions for each level of reasoning development. All models assumed measurement invariance across time for the latent class indicators.

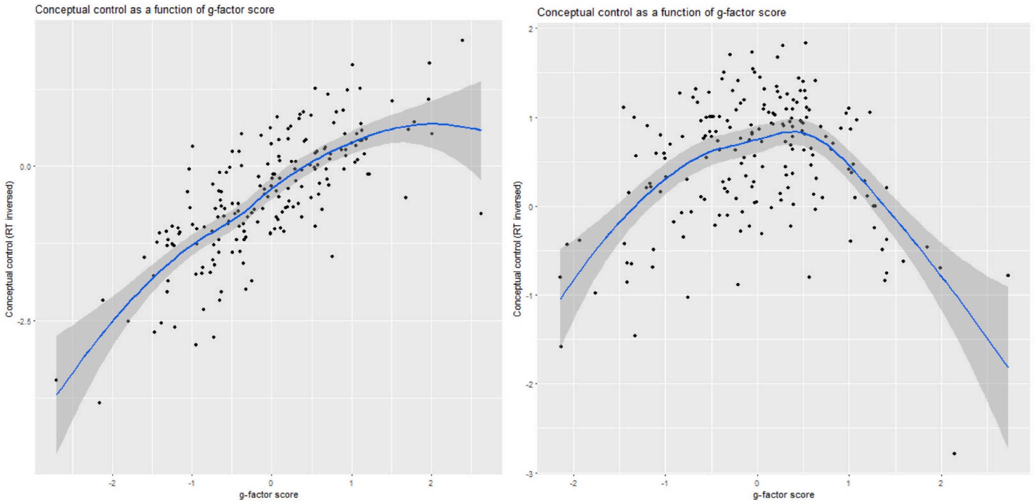
These models are summarized in Table 6. The fit of the model including the covariates was better in case of the first and the third developmental levels, as suggested by their smaller Bayesian Information Criterion (BIC). In the second level, the BIC of the model without the covariates was slightly lower but entropy, the index of classification accuracy of the models, was better (0.87 vs. 0.89), suggesting that this model classifies individuals better than the other model. Table 6 shows the influence of the covariates on transition. The crucial variables for transition to Level 1 were the four attention control measures and the simpler of the three working memory tasks, visuo/spatial working memory: the odds of transitioning to Level 1 were extremely high (>1000) for all four covariates, and very low for WM$_{IR}$ and WM$_{EX}$. Interestingly, the transition profile of Level 2 was similar but weaker than the transition profile of Level 1. Specifically, the two attention control factors were still influential (odds for perceptual, 7.13, and conceptual control, 5.13, were moderate) but only the influence of visuo-spatial working memory was significant (odds = 54.42). The transition profile of Level 3 was different: the critical influences for this transition originated from conceptual control and the two executive working memory tasks (all odds >50). Clearly, transition to each reasoning level was associated with different attention control and working memory profiles. The implications are discussed below.

Phase 1: 6 to 8 years

Phase 2: 9 to 12 years

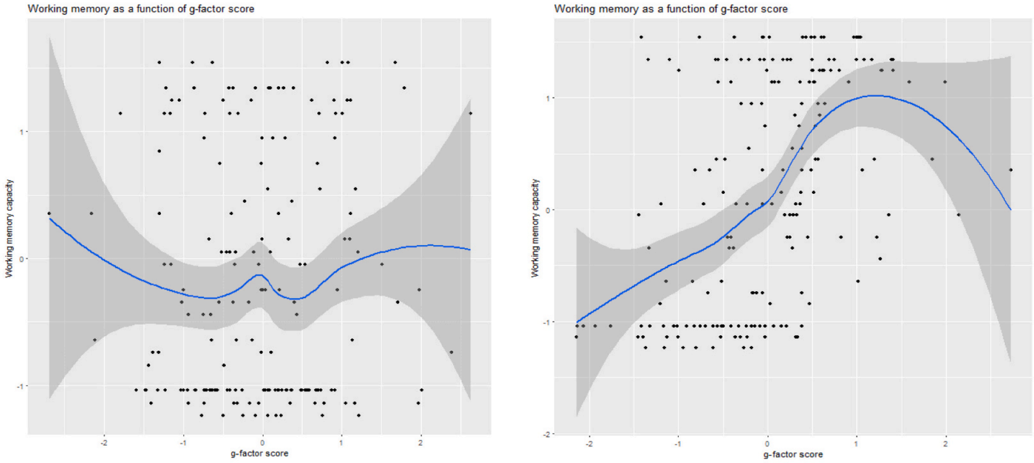
A. Conceptual control; $R^2 = .58$

$R^2 = .34$



B. Working memory; $R^2 = .01$

$R^2 = .24$



C. Analogical reasoning; $R^2 = .02$

$R^2 = .41$

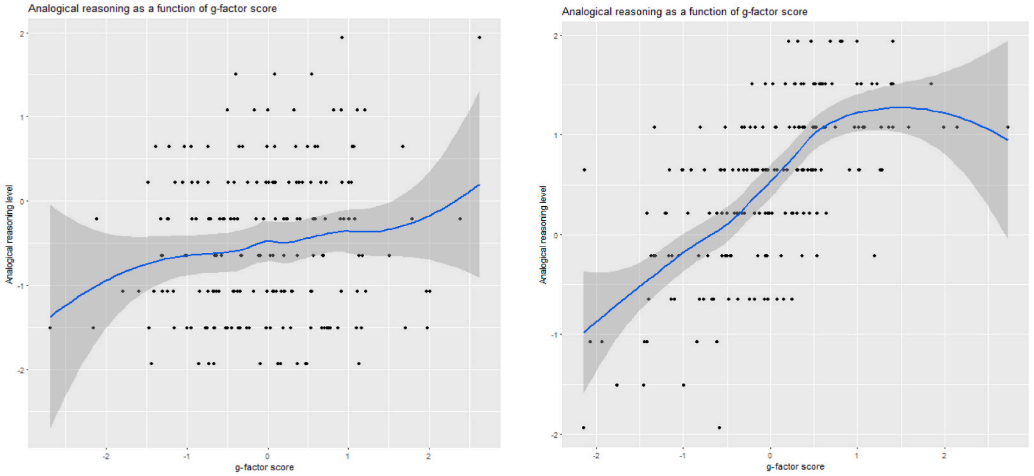


Fig. 4. Relation between individual processes and factor score on g as a function of developmental phase.

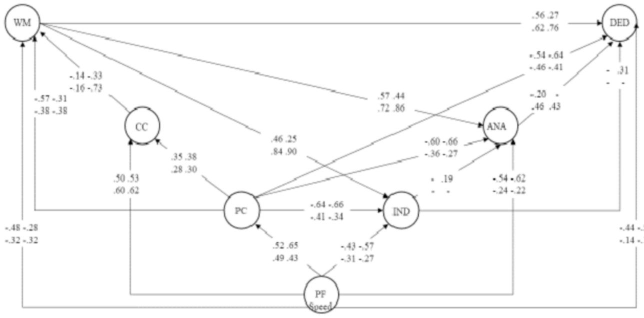


Fig. 5. The structural equation of the model of the relations between processes as a function of age group.
Note. The top numbers refer to the younger and the bottom refer to the older age group. The left column comes from the model where relations were free to vary between groups; the right column comes from the model where relations were constrained to vary in discrete ranges.

4. Discussion

All processes changed. Change patterns suggested two phases, one from 6 to 8 and another from 9 to 12 years. Some processes (i.e., attention focus and inhibition) changed faster in the first phase and others (i.e., conceptual control, working memory, and reasoning changed faster and developed extensively in the second phase). Clearly, rule-based thought emerged in the first phase but consolidated in the second. g was strong throughout the period from 6 through 12 years, but its relations with the various processes differed in each phase. Each process intertwined with g when dominating as a developmental priority and differentiated from it when new priorities emerged. Obviously, neither the prediction assuming overall differentiation nor the prediction assuming overall integration were supported. Relations between processes, in a remarkable convergence between cross-sectional and longitudinal findings, replicated the phase-specific profiles of g (Demetriou et al., 2017) and highlighted causal relations between processes, in line with predictions 2 and 3 derived from developmental priority theory. Therefore, the primary force of differentiation in this phase is a formative process transforming g, each time integrating the different processes. It is not investment of the available mental capital in different domains. This force may operate later, in adulthood.

Causal relations ran primarily bottom up. Overall, transfer of change ran from attention to both working memory and reasoning and from working memory to reasoning. However, precise effects varied between phases. In the first phase, attention control was the dominant force primarily driving changes in working memory. Transition to Level 1 reasoning, yielding early rule-based thought, was strongly depended on improvements in all aspects of attention control but minimally on changes in working memory. In the second phase, conceptual control and working memory were the major force. Transition to Level 2, resulting in more complex rule-based thought, was still drawing on the processes dominating in the first phase, but not as strongly as before, perhaps predating the next transition. Transition to Level 3 required improvement in attention control directed to information in memory despite perceptual interference and working memory requiring concomitantly executing a mental operation storing its products. We remind that Level 3 required awareness of inferential rules and their assembly according to a plan. Thus, the crucial factor in this transition was an explicit conceptualization of rules and their relations, reflected in conceptual control and working memory operating according to rules.

Earlier research showed that explicit awareness of inferential processes emerges as one of the formative factors of g in this phase (Kazi et al., 2019; Makris et al., 2017; Spanoudis et al., 2015). Also, awareness of logical schemes and learning to construct mental models for them was found critical in the transition from late rule-based to principle-based reasoning (Christoforides, Spanoudis, & Demetriou, 2016). These findings highlight how Spearman's (1927) first law of g, apprehension of

Table 6
Relations of the transition factor (from failure to success) of each of the three reasoning levels with the attention control and working memory processes.

Level	Covariate	Coefficient	SE	Z	*P*-value	Odds ratio
1	Perceptual focusing	62.04	9.56	6.49	0.00	>1000
	Perceptual Control	45.78	4.50	10.18	0.00	>1000
	Conceptual Control	29.63	2.89	10.25	0.00	>1000
	Perceptual WM	20.14	2.18	9.24	0.00	>1000
	Working memory 1	−3.35	0.43	−7.72	0.00	0.00
	Working memory 2	0.50	0.34	1.45	0.00	0.25
2	Perceptual focusing	−3.44	3.28	−1.05	0.30	0.03
	Perceptual Control	1.96	2.07	0.95	0.34	7.13
	Conceptual Control	1.64	1.70	0.96	0.34	5.13
	Perceptual WM	3.10	1.56	2.56	0.01	54.42
	Working memory 1	−0.19	0.18	−1.01	0.31	0.83
	Working memory 2	0.12	0.17	0.75	0.45	1.12
3	Perceptual focusing	−53.84	8.62	−6.24	0.00	0
	Perceptual Control	−60.30	4.25	−14.20	0.00	0
	Conceptual Control	8.95	1.97	4.54	0.00	7680.26
	Perceptual WM	−1.24	0.62	−1.99	0.05	0.291
	Working memory 1	4.16	0.54	7.69	0.00	63.87
	Working memory 2	7.16	0.85	8.46	0.00	11,282.34

Note 1: Perceptual discrimination was omitted from these models in sake of simplicity. Extremely high odds are denoted as >1000, implying certainty of transition under the given effect.
Note 2: The models were tested separately for each of the three reasoning levels.
Fit for Level 1 models: No covariates: H0 scaling correction factor for MLR = 1.09 ABIC = 2197.16; AIC = 2228.21; entropy = 0.74. With covariates: H0 scaling correction factor for MLR = 1.02 ABIC = 2164.80, AIC = 2198.70; entropy = 0.84; transition probability for movers = 0.54; transition probability for movers in the purified model = 3.17.
Fit for Level 2 models: No covariates: H0 scaling correction factor for MLR = 1.05, BIC = 2336.72, AIC = 2370.16; entropy = 0.87. With covariates: H0 scaling correction factor for MLR = 1.05, ABIC = 2340.21, AIC = 2376.51; entropy = 0.88; transition probability for movers = 0.48; transition probability for movers in the purified model = 4.46.
Fit for Level 3 models. No covariates: H0 scaling correction factor for MLR = 1.06 BIC = 1905.05, AIC = 1937.52; entropy = 0.85. With covariates: H0 scaling correction factor for MLR = 0.96 BIC = 1902.01, AIC = 1937.35; entropy = 0.86; transition probability for movers = 0.36; transition probability for movers in the purified model = 0.78.

experience, and Karmiloff-Smith's (1992) representational redescription may operate. Recent research suggested that experience is apprehended with increasing precision and clarity via increasingly accurate mechanisms of awareness which are gradually integrated into the spontaneous operation of g (Demetriou, Golino, et al., 2021; Kazi et al., 2019; Spanoudis et al., 2015). Recent research showed that mastering language in preschool is a rich source of mental awareness dominating other sources of awareness. This research showed that early linguistic awareness dominates over theory of mind and perceptual awareness in preschool. Notably, the mediational role of cognizance in the period from 5 to 8 years is stronger than in the period from 9 to 12 years (Demetriou, Spanoudis, et al., 2021).

These patterns necessitate highlighting the functional relations between cognitive processes in successive developmental phases. Mastering attention control beyond a certain limit provides the mechanism needed to focus on representations, align them, and search them systematically in sake of processing their relations. This is reflected in the fast expansion of visuo-spatial memory in this phase. In turn, these attainments generate representational raw material that may be searched and connected by rules. Representational proliferation strengthens the need for executive processes enabling to organize representations according to mental goals and reduce them into rules that may direct search and further interlinking. Mastering these processes in the second phase sets the background for Level 3 reasoning, indicating canonization of the inferential process. These findings are in line with research showing that the role of a process may vary with development. Engel de Abreu, Conway, and Gathercol (2010) found that in preschool and early primary school attention control processes involved in working memory tasks account for relations between working memory and fluid intelligence. Shahabi, Abad, and Colom (2014) found that short-term memory is more important as the liaison between working memory and intelligence at 8 years, but rule-based mental flexibility was more important at 12 years.

Therefore, this study suggested that there is validity in the interactive conception of g. We do need to invoke multiple processes to account for actual cognitive performance on any task at any time. However, interaction is driven by different processes in successive developmental phases. The processes dominating in each phase define how meaning is made in each phase. Thus, the interactive aspect of g is primarily a *formative developmental process,* guided by the process dominating. The processes dominating in a phase, once this phase is over, are integral functions of g. Therefore, noetron as a meaning-maker is redefined in each phase. It processes phase-specific representations and abstracts phase-specific relations. Preschoolers act intelligently when they can focus attention and attain behavioral goals, becoming gradually aware that their relationship with the world is mediated by mental states. Early primary school children behave intelligently when they can represent the products of their focus with relative accuracy and reason about them. Late primary school children show intelligence when they use reasoning to grasp new concepts and use them to solve novel problems. Adolescents behave intelligently when they can resist deception and uncover truth beneath appearances. In short, noetron expands by integrating increasingly efficient levels of control, going from episodic to representational to inferential to truth control. Reasoning and problem solving in different domains are partly overlapping languages to be learned in each domain. Cognizance in each phase is a mirror of the processes dominating the formation of g in this phase.

4.1. Limitations

Any study is limited in some respects. Here only a part of development was investigated. It would be ideal to include younger and older participants than the participants examined here to investigate if the patterns of relations observed are present in other developmental periods. It would also be useful to have more testing waves in the longitudinal study to examine how the present causal patterns extend in other ages. More testing waves would also allow to capture change across longer time intervals between testing times; this is needed to allow transformations in g to emerge and consolidate. Ideally, this study would be more able to explain transitions if metacognitive measures were involved that would highlight how awareness contributes to developmental transitions. Finally, the findings about differentiation found here would be strengthened if the patterns of differentiation identified would be verified by other methods, such as network modeling and local structural equation modeling. These methods would show that the centrality of different mental processes in a common structure, such as g, changes with age as a function of their phase-specific integration in g (Hartung et al., 2020). Hopefully, these concerns will be satisfied by future research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.intell.2021.101602.

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