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Mapping the Dimensions of General Intelligence: An Integrated Differential-Developmental Theory

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Abstract

We present a theory of mental architecture and development focusing on general intelligence (g). The theory integrates psychometric and developmental theories of intelligence into an overarching framework. The paper first focuses on the composition of g. It is shown that g involves attention control, flexibility, working memory, cognizance of mental processes, and inference. We then present a model of intellectual development involving four cycles – episodic, realistic representation-based, rule-based, and principle-based thought – and summarize several studies showing how the processes involved in g interact in each cycle. We then present research aiming to increase intelligence. Finally, we discuss the implications of this theory for psychometric, cognitive, and developmental science and show how it solves long-standing theoretical and practical problems not solved by other theories, such as the decreasing likelihood of attaining high intelligence, the differentiation of abilities with development, and the training fade-out problem.

The human mind has been the focus of several research traditions in psychology, each emphasizing some aspects of it more than others. Although all of them are still active and thriving within their boundaries, they leave important questions open partly because research within single perspectives misses important phenomena lying at their crossroads. Differential research uncovered stable dimensions of individual

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differences, such as general intelligence (i.e., inferential power applied to novelty), and a few strong domains of performance, such as verbal or spatial intelligence [Carroll, 1993; Jensen, 1998], but underestimated their development. Psychometric theories consider intelligence a stable trait of individual differences rather than as a developing construct. As a result, they do not elaborate on its development. Developmental research mapped changes in intellectual possibilities through the life span [Case, 1985; Demetriou, 1998; Piaget, 1970] but underestimated individual differences in development. For instance, developmental theories do not systematically specify the mechanisms causing differences between individuals in developmental rate or developmental end point. Cognitive psychology mapped cognitive mechanisms, such as working memory [Baddeley, 2012] and reasoning [Johnson-Laird & Khemlani, 2014], but did not specify how these mechanisms differ between individuals or ages.

Understanding the mind as a whole requires a theory that would accommodate its organization and development, individual differences in both, and learning at different phases of development. This article summarizes one such theory. The article is organized in four parts, focusing on (a) the composition and organization of processes in g; (b) their development; (c) changes in the relations between processes with development, and (d) learning. In each section we first summarize the fundamental postulates and findings of earlier theories and research and then present our model and related empirical research. Finally, in the concluding section, we discuss the implications of this theory for general cognitive and developmental science and show how it solves long-standing theoretical and practical problems not solved by other theories.

General Intelligence

Psychometric Theory

In current psychometric theory, the integration of the Cattell and Horn [1978] model of fluid and crystallized intelligence with Carroll's [1993] 3-stratum model (often referred to as the Cattell-Horn-Carroll model (CHC) is the dominant model of the architecture of the human mind [see McGrew, 2009]. According to this model, the human mind is organized in three hierarchical levels. The first level involves many specific abilities or skills in various domains. These are organized, at the second level, into eight broad abilities, each identified by a few underlying mental processes shared by all first-level domain-specific abilities. They are as follows: fluid intelligence (Gf), reasoning, crystallized intelligence, general memory and learning ability, broad visual perception, broad auditory perception, broad retrieval ability, broad cognitive speediness in dealing with problems such as rate of test taking or numerical facility, and processing speed, such as simple reaction time, choice reaction time. These in turn are constrained by general intelligence or g [Carroll, 1993; Cattell & Horn, 1978; Gustafsson & Undheim, 1996; Jensen, 1998].

Technically speaking, g stands for a common factor underlying the positive manifold, the fact that all cognitive tests correlate with each other. At the theoretical level, some theorists claim that g is a construct causing the positive manifold [Jensen, 1998]. Psychologically, the nature of g is under dispute since it was invented by Spearman [1927]. For Spearman [1927] himself g primarily stands for a powerful inferential competence underlying the eduction of relations and correlates. This is relational thought abstracting (a) relations between objects or events based on their similarities and (b) relations between relations based on the reduction of similarities into higher-order concepts [Carroll, 1993; Jensen, 1998]. Evidence amassed since the publication of Carroll's model suggests that g "is a worldwide phenomenon; is highly heritable; provides the common spine for all cognitive tests, complex or elementary, seemingly different or not; and has pervasive correlates throughout the body, brain and behavior" [Gottfredson, 2016, p. 120].

Many empirical studies operationalized Spearman's eduction competence in reference to tests of various forms of analogical reasoning, such as Raven's Progressive Matrices, which in turn, was identified with Gf. This research showed that g (as it emerges from many stratum-2 factors) is practically identical with Gf [e.g., Gustafsson, 1984]. Later research sought to reduce g (and Gf) to more basic processes. Jensen [1998, 2006] stressed information-processing speed, defined as the minimum time required to identify a simple stimulus or execute a mental act according to a goal. According to Jensen, processing speed is an index of the quality of information processing in the brain. Jensen [1998] reported a correlation of about 0.5 between g and information-processing speed. Based on 172 studies conducted over a period of 50 years, Sheppard and Vernon [2008] found that the correlations between information-processing speed and g, although always present and systematic, are moderate, ranging around 0.3, tending to strengthen with increases in the complexity of reaction time tasks. Current brain research suggests that several aspects of brain functioning, such as connectivity and efficiency, do relate to both speed and g [Haier, 2017]. However, this relation is much weaker than it would be expected if g would be identified with information-processing speed.

Other research suggested that working memory capacity (WMC) is a key component of g. WMC is the ability to hold information in an active state while integrating it with other information until the current problem is solved, according to a goal (e.g., recall the second last number of each of a set of numbers heard before or recall the numbers backwards). The major component here is the representational efficiency in implementing the organizational process and the flexibility in shifting between the results of its application at a given step and earlier results, given the demanding time constraints of these tasks. Many studies did show that g or each of its component competences, such as inductive and deductive reasoning, are highly related with working memory [Cornoldi & Giofrè, 2014; Kyllonen & Christal, 1990]. Indeed, relations between g and WMC are higher than relations with information-processing speed but not as high as it would be expected if g and WMC were isomorphic. Based on the meta-analysis of a large number of studies, Ackerman, Beier, and Boyle [2005] found that the average true correlation between working memory and g is 0.48.

However, it might be the case that the relations between WMC and g are moderated by information-processing speed. Ackerman et al. found that the speed–WMC relations are higher than with g (0.57). Indeed, Chuderski [2013] showed that the WMC–g relation varies as a function of the demands of the problem-solving situations: the more one performs under conditions of fast decision-making, the higher the g–WMC relations, varying from 0.62 (performance on Raven and analogy tests without time constraints) to 1 (performance on the same tests under highly speeded conditions). What might be common between WMC, Gf, and choice reaction time tasks? There is no agreement in answering this question. Some authors maintain that

WMC is needed to establish and maintain bindings between stimulus and response representations, especially when the mapping between stimuli and responses is arbitrary so that earlier learning cannot help to choose a response [Wilhelm & Oberauer, 2006]. However, others suggested that WMC and Gf involve processes that are not causally related. Rather they are organized around top-down processing goals: WMC allows the person to represent information so that solutions can be envisaged, and Gf involves the ability to disengage from rejected solutions and envisage new ones [Shipstead, Harrison, & Engle, 2016].

Envisaging and choosing between solutions led scholars to introduce another crucial component of g: executive control [Blair, 2006]. This is the ability to focus processing on goal and flexibly deploy a plan for attaining it in spite of possible interference. Thus, executive control involves attention focusing, inhibition, and flexibility in shifting. However, the relations between each of these functions and g or IQ, although significant and systematic, are also moderate, varying circa 0.3 [Arffa, 2007]. Therefore, executive control, like information-processing speed and WMC, did not emerge as a privileged representative of g.

In response to this state of affairs, several scholars stripped g of any distinct psychological process. In the words of Kovacs and Conway, “there is no psychological process that corresponds to psychometric g” [2016, p. 171]. Rather, g is an algebraic consequence of the interaction between specific processes. This interactionist approach comes in two versions. Kovacs and Conway [2016] suggested that g emerges as a result of many processes sharing the same process, executive control. This does not necessarily reflect actual common elements between different processes but the state of the common process called upon, which acts like a bottleneck marking individual differences in various specific abilities. As already noted, placing executive control in the center of process overlap would imply that the relation between g and executive control would be much higher than found by the studies summarized above.

Alternatively, van der Maas et al. [2006] suggested that the positive manifold is not caused by any of the processes above per se. Rather it emerges purely by their interactions during development. That is, the correlations between processes underlying g reflect their interactions as they are jointly brought to bear on problems rather than any single process alone. Thus, the power of g would increase with age to reflect strengthening of the interaction between processes. However, this prediction assumes a linear increase in g with age, which is not the case. We will show below that g recycles with development thereby always playing a strong role through the life span [Demetriou, Christou, Spanoudis, & Platsidou, 2002; Demetriou, Mouyi, & Spanoudis, 2008; Gignac, 2014]; this reflects the operation of processes orchestrating the interactions [Demetriou & Spanoudis, 2018].

Empirical Mapping of the Dimensions in g. To capture the substance of g, a study would have to satisfy three requirements: first, psychometric g would have to be abstracted from a wide array of mental competences, such as the stratum-2 broad abilities in the CHC model; second, the relation between g and each broad competence would have to be independently specified; third, the relation between each of the broad competences and general information processing (i.e., attention control, shifting, working memory) supposedly shared by them would also have to specified.

We conducted several studies according to these requirements. One of them involved participants from 9 to 15 years of age who were examined on four types of

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competences [Makris, Tachmatzidis, Demetriou, & Spanoudis, 2017]. First, several aspects of reasoning – deductive (transitivity and conditional reasoning), inductive (verbal analogies), quantitative (algebraic reasoning and numerical analogies), causal (combinatorial reasoning and hypothesis testing) – and spatial reasoning (various aspects of mental rotation). Second, several aspects of language competence: syntax (construct syntactically correct sentences out of scrambled words), semantics (arrange scrabbled sentences into a meaningful story or understand ready-made stories), and vocabulary (define words or specify the meaning of words). Third, several aspects of processing efficiency and executive control: attention control (Stroop-like inhibition tasks), flexibility in shifting (dimensional change sorting tasks), and working memory (forward verbal and digit span and visuospatial working memory).

Finally, a key process examined in this and the other studies to be discussed below is cognizance. Cognizance is the part of consciousness applied to cognitive processes; it is the process of becoming conscious of mental content (e.g., "I know that I am thinking about numbers") and cognitive processes (e.g., "I know that I am looking for the bigger number in a series," "I knew this information," etc.) and reflecting on and evaluating them vis-à-vis a goal. Specifically, this study involved several measures of self-awareness and self-evaluation related to performance on each of the reasoning domains mentioned above. After solving each of the reasoning tasks above, participants evaluated their own success on and the difficulty of each task. To make these evaluations comparable to performance scores, these scores were transformed into evaluation accuracy scores reflecting concordance of evaluations to actual performance on the respective tasks [Demetriou & Kazi, 2006; Kazi, Demetriou, Spanoudis, Zhang, & Wang, 2012; Makris et al., 2017].

Performance on these batteries was modelled by a series of structural equation models designed to satisfy the three requirements specified above. For the sake of this aim, we created a first-order factor for each of the domains outlined above. To satisfy the first requirement above, we created a second-order factor that was related *to all domain-specific language and reasoning factors but one;* this factor stands for g. To satisfy the second requirement, in a series of models, this second-order g factor was regressed on the domain-specific factor left out of it. Therefore, the domain-specific factor was lifted up to the status of a reference factor or a proxy that may speak about the identity of the common factor. That is, a high relation between g and the reference factor would indicate that g carries the constituent properties of the reference factor. Finally, to satisfy the third requirement above, the reference factor was regressed on attention control, cognitive flexibility, and working memory. This manipulation may show whether any of the reference factors was a privileged mediator between g and the supposedly shared processes. An idealized illustration of this model is presented in Figure 1.

Each of the theories summarized above leads to different predictions about the pattern of relations expected. The theories assuming that some specific processes are involved in g more than others would predict that the reference factors standing for these processes would have a higher relation with g than the other processes. For instance, Gf [Gustafsson, 1984; Spearman, 1927] or syntax in language [Carruthers, 2002] would emerge as stronger proxies of g than each of the other factors. Interactive or mutualist models would predict that the relations between g and reference factors would vary with the complexity of the interactions involved in each reference factor: the higher a factor's complexity, the higher its relation with g [van der Maas et al.,

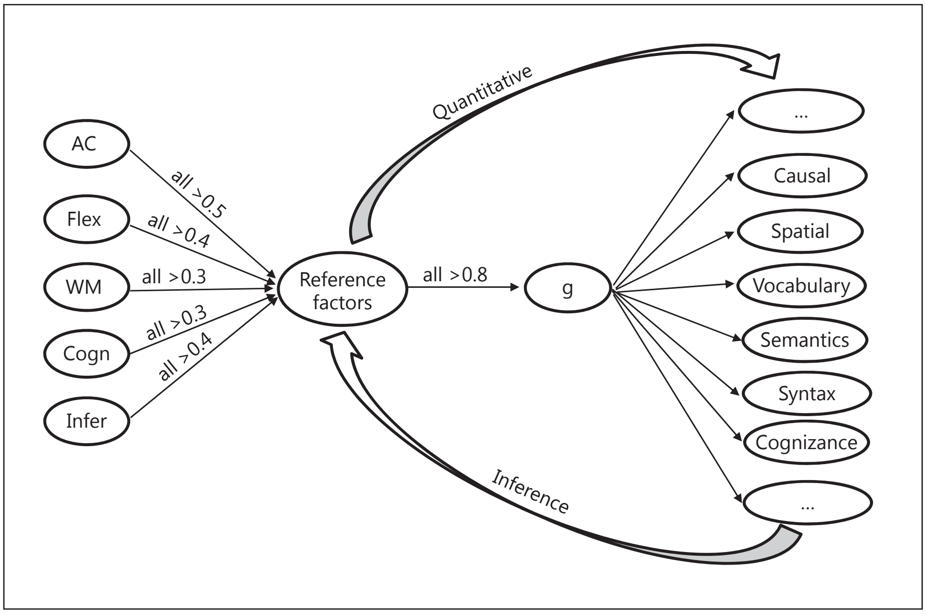

Fig. 1. An idealized model of the structural relations between g and each of the reference factors and between each of the reference factors with attention control (AC), cognitive flexibility (Flex), working memory (WM), cognizance (Cogn), and inference (Infer). The figure summarizes eight models in which first-order factors standing for each of the domains specified but one (the reference factor) were regressed on g, g was regressed on the reference factor, and the reference factor was regressed on the factors standing for aspects of executive control, plus cognizance and inference. The arrows from first-order factors to the reference factor and vice versa indicate that all first-order factors were used, in turn, as the reference factor.

2006]. For instance, in the present study, some of the domains involved are highly specific and some are very broad. In language, syntax (rules about sentence structure) is more specific than semantics (grasping meaning at various levels). In reasoning, spatial reasoning (specific processes executed on mental images) is simpler than causal reasoning (inferential processes integrating hypotheses with evidence and testing processes). Finally, theories assuming a ubiquitous common core (whatever this might be) would predict that the relations between g and the reference factors would be similar across processes, because the same core is involved in each of them.

We found that the relation between all reference factors and g was always very high (all >0.8). Contrary to the privileged process theory, there was no privileged reference factor. Contrary to the mutualist models, the very small differences between reference factors and g cannot differentiate any of the factors with respect to complexity. However, these results align with common core theory because they were all very high regardless of differences in the processes represented by them. The relations of the reference factor to each of the three executive processes were in the same direction. They were all in the same range (0.4–0.6) and very similar across reference factors.

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To map the processes in g, two other models were tested. In the first model, all reasoning and language factors were regressed on g, and g was regressed on the three executive processes as well as cognizance. In this model, cognizance was taken as an independent factor together with the three executive processes to examine if cognizance differentially contributes to g. The four factors accounted for 27% (attention control), 18% (flexibility), 27% (working memory), and 7% (cognizance) of the variance of g, amounting to a total of 79%. In the second model, the reasoning factor was also taken as an independent factor so that g was regressed on the four factors above and reasoning. It is stressed that adding reasoning to the predictors did not affect the relation between g and the other factors. But it did add an additional 19% to the variance of g accounted for by the predictors, resulting in a total of 98%. This is very high. Therefore, attention control, flexibility, working memory, cognizance, and inference (i.e., deductive and inductive reasoning, standing for Gf) are strong and independent building blocks of the common core identified with g. Attention is drawn to the fact that g so decomposed fully exhausted variation in all first-order domain-specific reasoning and language factors. In a more formal language, g might be defined as follows:

$$g = f\,(\text{attention control} + \text{flexibility} + \text{working memory} + \text{cognizance} + \text{inference}).$$

State of the Art about the Composition of g. The research summarized above explicates why none of the processes invoked as the causal core underlying g was able to account for the state and functioning of g on its own. *Each and every one is needed*; g is a focus, search and align, cognize and choose, reason and abstract mechanism. Each of the processes involved (executive control, flexibility, working memory, cognizance, and inference), at any age, is autonomous and a distinct contributor to g. It might be the case that the relative contribution of each of these processes to g varies with development. This is the question of the next section.

Developmental General Intelligence

Is There a Developmental g?

Strictly speaking, psychometric g is not a developmental construct, and it is considered to be generally stable from early childhood to middle age. In classical developmental theory intelligence changes qualitatively so that individuals at successive stages or levels of cognitive development can build different kinds of concepts about the world and solve different kinds of problems. Transition across levels is controlled by a central mechanism that defines both the understanding and problem solving that is possible at a given time and their modification. In Piaget's theory, intelligence interrelates by assimilating new information into existing schemes and accommodating these schemes to the novelties of new information; it develops by equilibration, which reintegrates mental processes at higher levels of abstraction [Piaget, 1970].

These processes are impressively similar to Spearman's eduction of relations and correlates mechanism. They both powerfully constrain mental functioning across age phases or individuals, respectively. In fact, empirical research showed that Piagetian tasks are strongly interrelated giving rise to a psychometric-like g. This Piagetian g persists in time coordinating developmental change longitudinally [Bradmetz, 1996], and it relates highly to psychometric g [i.e., 0.88; Lautrey, 2002]. In our research, developmentally inspired tasks and Wechsler tasks correlated highly (0.62) and loaded on the same stratum-2 broad factors [Case, Demetriou, Platsidou, & Kazi, 2001]. These commonalities are expressed in the fact that Carroll [1993] included "Piagetian reasoning" in the domains of reasoning involved in Gf.

However, there is an addition that is clearly original with developmental theory. Each time a child's attempt at assimilation runs into contradictions, the child looks for new possibilities by accommodating previously ignored reality characteristics. The balance (equilibration) between assimilation (recognition of similarities) and accommodation (recognition of differences) and induction of relations is based on a double reflection mechanism that allows elaboration on similarities and relations between present encounters and available related representations and their concatenation into the newly accommodated schemes. Piaget [1977/2001] might see in these two aspects of cognizance his two aspects of abstraction: reflective and reflecting abstraction, respectively. This mechanism generates increasingly flexible (reversible) mental structures allowing understanding of stability and change in the world and grasping the (physical or logical) implications of alternative physical or mental actions. In development, these changes result in increasing resistance to deception of appearances, flexibility in interrelating mental operations, and efficiency in reducing them to logically and conceptually overarching cohesive systems and structures.

Unsurprisingly, reductionist endeavours in developmental research matched psychometric reductionism. That is, researchers attempted to reduce stage changes in the reasoning processes mentioned above to general information-processing mechanisms. Some scholars suggested that changes in speed of information processing drive changes in reasoning [Kail, 2007]. Neo-Piagetian theories associated transitions along cognitive development stages to changes in working memory [Case, 1985; Halford, Wilson, Andrews, & Phillips, 2014; Pascual-Leone, 1970]. However, developmental relations between reasoning and these information-processing constructs proved to be very similar to the relations found by individual differences research. Specifically, age-related changes in processing speed are related to concurrent changes in reasoning, but this relation (between 0.2 and 0.4) is not strong enough to consider speed as the major driver of intellectual development [Carlozzi, Tulsky, Kail, & Beaumont, 2013; Kail, Lervag, & Hulme, 2015].

Regarding working memory, relations between progression along cognitive developmental sequences and increases in working memory do exist [Cowan, 2016; Demetriou et al., 2002]. However, working memory is not the transition mechanism as assumed by neo-Piagetians. For this to be the case, the cognitive level of children in reasoning would have to be as expected according to their level of working memory rather than sheer age. For instance, two children of different ages but the same WMC would have to operate on the same cognitive developmental level. This is clearly not the case. Demetriou et al. [2013] showed that reasoning attainment matches age rather than working memory level. We allocated children of every age between 4 and 16 to three groups according to their performance on various working memory tasks, low (0–2 items), medium (2–5 items) and high (5–7 items), and compared their performance on several reasoning tasks. The main findings are summarized in Figure 2. It can be seen that the reasoning performance of children with high WMC was

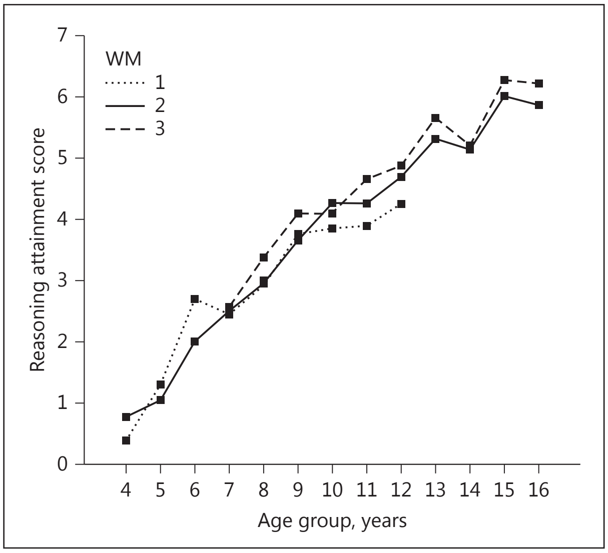

Fig. 2. Reasoning attainment as a function of age and working memory (WM) level (1 = low, 0–2; 2 = medium, 2–5; 3 = high, 5–7). [Based on Fig. 5, Demetriou et al., 2013].

closer to the performance of their age mates with low working memory rather than to performance of older individuals.

Following the fashion of time, eventually, executive control came to dominate recent research and theory as the main motor of intellectual development [Diamond, 2013; Zelazo, 2015]. This line of research assumes that reflection and awareness drive executive control, which in turn drives the development of more complex processes, such as working memory, theory of mind, cognitive flexibility, and reasoning. According to Zelazo [2015], the development of executive control is made possible, in part, by increases in the efficiency of reflective reprocessing. This allows children to shift between rules and abstract their similarities thereby building rule hierarchies of increasing complexity. Again, evidence suggests that changes in executive control do play a role in cognitive development. However, this role varies with age: it is very high (approx. 0.8) in the 3- to 6-year period but lower (approx. 0.3–0.5) in the 8- to 15-year period [Zelazo et al., 2013].

A hierarchical cascade was proposed by Fry and Hale [2000] as a model for the relationship between these processes. This model postulated that each process is embedded into the next more complex process in the hierarchy (Fig. 3a). 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]. 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, 2016]. Reasoning and problem solving in different domains resides higher because it involves, additionally, inferential processes interrelating representations for the sake of valid conclusions [Johnson-Laird & Khemlani, 2014].

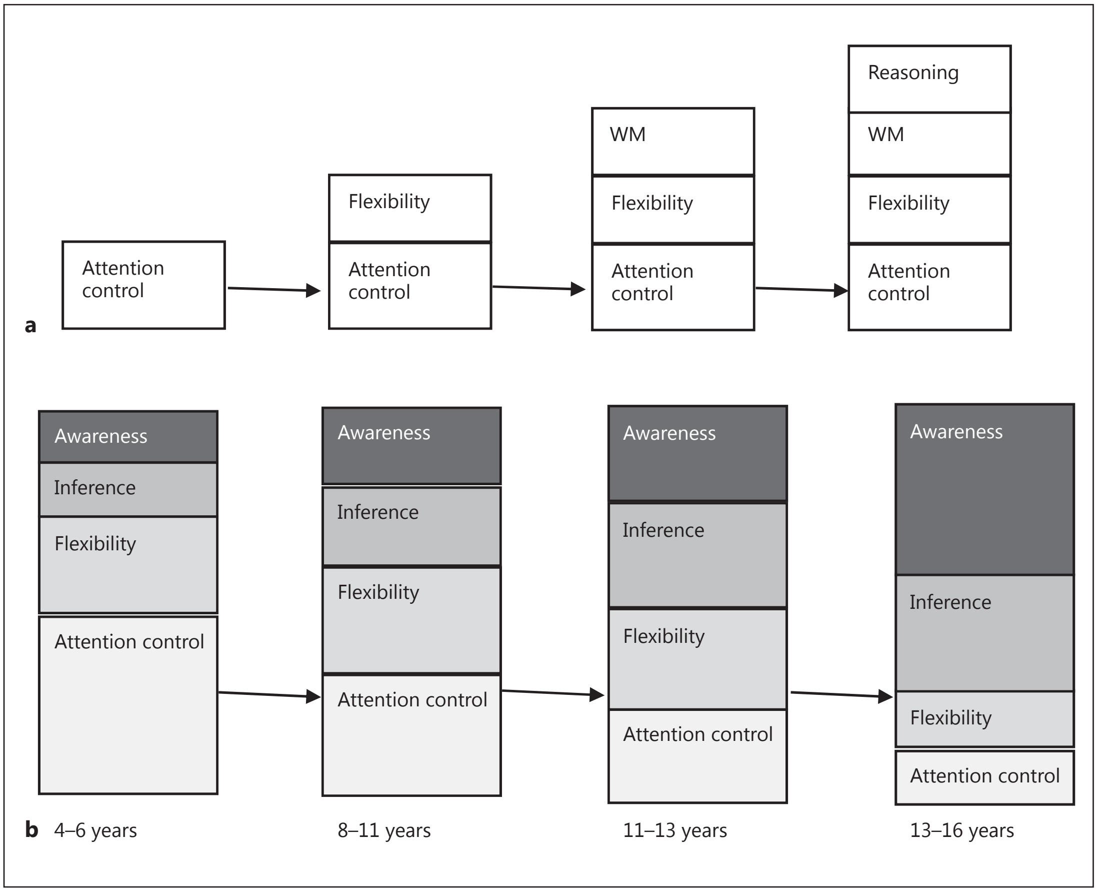

Fig. 3. Models of relations between processes: the classical cascade and the developmentally sensitive cascade model of relations between processes varying with developmental phase. WM, working memory. **a** Classical cascade model. **b** Developmentally varying cascade model.

However promising the cascade model appeared to be, it is weak in two important respects. First, Makris et al. [2017] showed that the cascade model as a hierarchy of simpler processes embedded into more complex processes (attention control (–0.64) → flexibility (0.58) → working memory (–0.89) → reasoning (0.87) → language (0.98) → cognizance (0.60)) cannot be discriminated from its inverse where more complex processes are embedded into simpler processes (cognizance (0.50) → language (0.67) → reasoning (0.97) → working memory (0.84) → flexibility (–0.84) → attention control (0.48)). This finding suggests that the same ensemble of processes is involved in all processes, probably at proportions varying with growth. Indeed, second, Makris et al. [2017] tested this model in three separate groups, which involved participants 9–10, 11–13, and 14–15 years old (Fig. 3b). They found that the relations between processes residing at the lower end of the cascade (attention control, flexibility, and working memory) decreased systematically across the three age groups, indicating their levelling off; the relations between processes residing at the higher end of the hierarchy (working memory, reasoning, language, and cognizance) remained stable or increased, indicating that they still develop. These patterns suggest a shift from executive processes related to control of attentional and mental focus in preschool to processes directly related to reasoning and explicit awareness in late childhood and adolescence. Therefore, relations between processes vary as a function of developmental phase, reflecting differences in the representational and procedural composition of g at successive developmental phases, suggesting that the cascade model does not differentiate between developmental phases.

Cycles in the Development of g

The research summarized above suggests that cognizance, reasoning, and various aspects of executive control are always present but with varying levels of contribution to developmental g, according to developmental phase. Research suggests that the relations between these processes are transformed over four major developmental cycles, with two phases in each. Major phase characteristics and developmental trends are illustrated in Table 1. New representations emerge early in each cycle, and their alignment dominates later. In succession, the four cycles operate with (a) *episodic representations* from birth to 2 years (remembrances of actions and experiences preserving their spatial and time properties), (b) *realistic mental representations* from 2 to 6 years (blueprints of episodic representations where spatial and time properties are reduced, associated with symbols, such as words), (c) *generic rules organizing representations* into conceptual/action systems from 6 to 11 years (e.g., concepts about categories of things, exploring causal relations), and (d) *overarching principles integrating rules* into systems where truth and multiple relations can be evaluated from 11 to 18 years (i.e., principles specifying how rules may be integrated). Changes within cycles occur at 4 years, 8 years, and 14 years, when representations become explicitly cognized so that their relations can be worked out, gradually resulting into representations of the next cycle [Demetriou & Spanoudis, 2018].

Below we will first summarize research highlighting the representational, executive, awareness, and inferential possibilities of the four cycles. We will then focus on research illuminating how changes in each of these processes relate with g in each developmental cycle. Finally, we will summarize research exploring how cognizance mediates between executive control and reasoning across the cycles.

Episodic Thought. Infants are mentalistic creatures [Baillargeon, Scott, & Bian, 2016; Carey, 2009]: they represent themselves and others as representational beings. Infants differentiate themselves from objects by the age of 5–6 months [Rochat, 1998], and they recognize themselves in the mirror by 15 months [Gallup, 1982], suggesting that they compare what they see with representations of their invisible body parts. Also, infants talk to themselves about earlier experiences suggesting that they reflect on them before they are 2 years old. For example, they repeat instructions given to them earlier by an adult [Vallotton, 2008].

By 15–18 months, infants show awareness of global blocks of action including an executive sequence where past actions are intertwined with perceptions and current actions: when encountering a familiar object set, they intentionally restore the sequence which involves representation of past experiences (e.g., insert objects of

Table 1. Milestones in the development of cognizance, executive control, and reasoning across developmental phases and cycles

Age	Cycle	Cognizance	Executive control	Reasoning
0 – 1	Emerging episodic representations	Differentiate self from objects	Stimulus-action links, re-instituting circular reactions	Episodic expectations, e.g., mother calling, she is coming
1 – 2	Integrated episodic representations	Face recognition Explicit awareness of stimuli and actions, implicit awareness of mental states	Perception initiated represented goals, e.g., insert objects in same-shape holes	Extrapolation of episodic sequences mimicking implication, e.g., Dad came, Mom is coming too
2 – 4	Emerging realistic mental representations	Awareness of perceptual origins of knowledge, implicit awareness of representations and one's own performance	Automation of self-initiated action episode, e.g., girl bathing her doll Instruction-based goal execution, e.g., bring my shoes	Translation of representational ensembles into reasoning sequences: uncle's car is outside, so he is in
4 – 6	Integration of realistic representations	Explicit awareness of representations/implicit awareness of mental processes, ToM	Control of attentional focus: shifting between actions according to instructions activating a represented plan	Pragmatic reasoning: You said I can play outside if I eat my food; I ate my food; I go to play outside
6 – 8	Emerging rule-based representations	Explicit awareness of representation/actions relations, implicit self-evaluation rules	Rule-based action plans, such as turn-taking in games	Scheme-based reasoning, modus ponens, conjunction, disjunction: there is a dog and a tiger; there is a dog, so there is a tiger
8 – 11	Integration of rules into rule-based systems	Explicit awareness of mental processes, 2nd-order ToM, logical necessity	Conceptual fluency allowing flexible shifting across conceptual systems: first recall fruits, then animals, then furniture	Biconditional reasoning, integrated modus ponens-modus tollens: if there is an apple there is a pear; there is an apple, so there is a pear; there is no pear, so there is not an apple
11 – 13	Emerging principle-based representations	Explicit awareness of mental processes; implicit self-evaluation principles	Automation of conceptual fluency programs: complex everyday plans, such as homework planning	Intuitive grasp of fallacies: if there is an apple, there is a pear; there is a pear; I cannot know if there is an apple
14 – 16	Integrated principles	Accurate self-representation and self-evaluation	Inferential relevance mastery program: long-term plans, such as study choices for university	Complete conditional reasoning; as above, also: if there is an apple, there is a pear; there is no apple, I cannot know if there is a pear

ToM, Theory of Mind.

various shapes in a toy turtle through same-shape holes) and projection into an action plan (e.g., grasp objects and look for same-shape holes, testing by trial and error if they do not get through). This is presorting episodic representation where perceptions, remembered representations, and actions reflected upon are intertwined. Also, infants infer that someone who saw where an object was hidden will look for it at that place [Onishi & Baillargeon, 2005].

Episodic reasoning involves reciting episodic representations (e.g., "I put this, and this, and this, all of them," preparing for conjunction; all = this + this + this) or reading them forward (e.g., "dad came, mom is coming too," preparing for implication; if A → B follows), abstracting what runs through them. When it concerns behavioural sequences related to a person (e.g., "Dad is going upstairs; he is going to get dressed"), the episode may appear as a belief understanding. The belief, however, is actually a reading forward projection of the episode for another person rather than an explicit representation of this person's mental states.

Realistic Representational Thought. Evidence suggests that representations at 2–3 years of age are reduced mental projections of episodic representations with a component of implicit awareness. Paulus, Proust, and Sodian [2013] trained 3-year-old children to associate individual animals with specific objects. They showed them short videos of an animal doing something (e.g., an elephant who likes watching TV). Sometime later they showed the probe animal (e.g., the elephant) and they tested if children remembered the object associated with it (a TV). They also asked the children to indicate how confident they were for their judgement. Confidence ratings for correctly remembered items were higher than ratings for incorrectly noted items, suggesting an awareness of representations stored earlier in memory. Children at this age are aware that when one saw or heard an object, one knows about it, suggesting awareness of the perceptual origins of knowledge (i.e., I know because I see, hear) [Flavell, Green, & Flavell, 1995]. This makes theory of mind possible at age 4, enabling preschool children to understand that one's actions relate to one's representations [Wellman, 2014]. Emerging insight into the nature of representations eventually brings them into focus, allowing for comparison and alignment.

At this age executive control is guided by a "scan-choose-focus-respond" program allowing preschoolers to set up action plans involving several steps to be implemented in succession and shift between stimuli and responses, according to a goal (e.g., say day when they see the moon and night when they see the sun [Vendetti, Kamawar, Podjarny, & Astle, 2015]). Compared to the task where infants' sorting objects is guided by the match between object shape and hole shape, this task involves a priori awareness of representations one may focus on and choose from, organizing action beforehand.

At this early phase, representations have a transparent relation to objects or events, and they function as ensembles of inference. As a result, relations at this early phase of development are intuitively "read out," so to speak, from the representational ensembles: "It's cloudy; it will rain; so we need our umbrella." Thus, 2-year-old children draw inductive inferences when perceptual patterns are clear enough so that missing components may be integrated, based on similarity or extrapolation of characteristics across objects [Gelman, 2003]. This is evident in language learning: associating an object with a novel name (i.e., "this is a dax" or "this is a diffle") leads 2- to 3-year-old children to infer that other objects of the same shape are "dax" or "diffle" [Becker & Ward, 1991]. Literally speaking, deductive inference does not exist at this phase. Plausible inductions complete activated experiential episodes without constraining each other, if not aligned. Thus, in this phase, the boundaries between categories are flexible, depending upon current dominant inductions. Even natural categories, such as "boy" and "girl" may not have fixed boundaries: Athina, at 34 months of age, wondered when Nicolas, her cousin, 31 months old, will grow up like her to become a girl.

At about the age of 3–4 children start to differentiate between representations or to be able to zoom in on their components. As a result, they can intentionally search for, scan them, and align them. For instance, they can solve simple Raven-like matrices where patterns vary along a single dimension. However, they still face difficulty in aligning patterns across two dimensions. Along this line Benoit, Lehalle, Molina, Tijus, and Jouen [2013] conducted an interesting study of the alignment between representations of quantities from 3 to 5 years of age: i.e., mapping dot arrays from 1–6 with number names and number digits. They showed that 3-year-old children can only map number words on arrays of up to 3 dots. They cannot map number words on arrays of 4–6 dots, dots with digits, or number words with digits. Obviously, they have a global representation of quantities within the subitization limit associated with corresponding number words as an ensemble. Representations from the three representational spaces become accessible as distinct mental entities that can be aligned at 4 years. Four-year-old children map both number words and number digits with arrays of up to 6 elements but do not map number words on digits. At age 5 children map representations with each other for all sizes.

When this is possible, children start to build concepts in the various domains: there must be at least two representations to conceive of a class (e.g., "our cat *is* an animal"), a quantity (e.g., "Anna has 3 and I have 2; she has *more than* me"), a causal relation (e.g., "Mary *spilled* the milk"), a spatial relation (e.g., "the toy car is *on top of* the book"), or make an inference. Alignment of representational blocks in this phase optimizes inductive choices and allows deals based on pragmatic reasoning: "We agreed I can play outside if I eat my food; I ate my food; so, I will go to play outside" [Kazi et al., 2012]. This sequence, which mimics modus ponens (if p then q; p, thus q), is basically an induction that locks two representations ("A occurs" and "B occurs") together into an inductive rule (i.e., "when A occurs, B also occurs"). Children may consider inductive options (i.e., "no eating – no play" and "eating – play") because their executive control program allows them to envisage alternative choices. This will be raised later into deductive inference.

Rule-Based Thought. At 6–8 years, children are explicitly aware of mental representations and their relations with their own actions. For instance, they differentiate between easy and difficult memorization tasks, suggesting awareness of the relation between complexity of representations and learning [Paulus et al., 2013]. In this phase, children also recognize that knowledge may be constructed by inferential extrapolation as well (i.e., I know because I can reason on what I saw, heard, etc.). Thus, in this phase, cognizance of the inferential aspects of knowledge takes over as the mediator between attention control and working memory, on the one hand, and reasoning, on the other [Spanoudis, Demetriou, Kazi, Giorgala, & Zenonos, 2015]. However, at this age, children do not yet explicitly differentiate between mental functions, such as memory and reasoning, nor do they explicitly associate each with specific processes (rehearsal vs. inference). This is possible at 8–10 years [Paulus, Tsalas, Proust, & Sodian, 2014], when there is an explosion of awareness of the mental world. Children in this phase differentiate between the metaphorical and literal meaning of verbal statements [Olson & Astington, 2013], master second-order theory of mind (e.g., "I know that George knows that Mary knows that …" [Wellman, 2014]), and recognize that lags in knowledge may be compensated by inference (e.g., "He sorted by color, so blue objects would be in the blue box" [Spanoudis et al., 2015]).

Children at 6–8 years do not prepare sufficiently to cope with a forthcoming task because they are not explicitly aware that different tasks require relevant preparation [Chevalier & Blaye, 2016]. However, in the next phase, at 8–9 years, awareness of different mental processes allows children to shift flexibly between them (e.g., to remember you need to observe carefully and rehearse; to sort you need to follow a sorting rule [Demetriou & Spanoudis, 2018; Demetriou et al., 2014, 2017]). In this phase, attention control and shifting emerge as strong predictors of reasoning. This is expressed in the upgrading of executive control from inhibition control into a *conceptual fluency program* allowing children to shift between mental processes (e.g., memory vs. inference) or conceptual domains (e.g., they recall words belonging to different categories following a probe: recall fruits, animals, furniture, in this order [Brydges, Reid, Fox, & Anderson, 2012]). Compared to the previous "focus-recognize-respond" executive program, the current program involves analytic representations of conceptual spaces and flexibility in variably running across them. One might argue that Piaget's [1970] reversibility is an index of this executive program.

In fact, early in the next phase, at 6–7 years, there is a shift from "realistic" representations that are visible to the "mind's eye" to the inferential threads interlinking them. At the beginning these may function as semantic blocks defining generic concepts, such as object classes, number, and causal attributions. The integration of various conceptual spaces related to number, such as object arrays, number words, counting, digits, etc., into a common mental number line is a good example of an underlying mental construct in the domain of quantitative reasoning [Dehaene, 2011]. Thus, in this phase, children can solve two-dimensional Raven-like matrices which require integration of two familiar and obvious dimensions (e.g., shape, size, background, etc.). Piagetian concrete operations in various domains (such as classes, quantities, length, weight, area, number, etc.) and their interrelations are a strong sign of this shift of thought from representations to their underlying relations.

In the next phase, at 8–10 years, another product of this emergent awareness is the implicit use of rules specifying how different types of inference are interrelated. Thus, children in this phase can solve Raven matrices which require deciphering critical dimensions by interpolation of missing features based on tentatively tried general rules: "It is the double of each last number," "it goes by one more," etc. Proper deductive reasoning requires evaluating a sequence of statements vis-à-vis a rule that prescribes how they *must* be related. Formally, if accepted that "A implies B," then two possibilities are necessarily true: when A occurs, then B occurs too, and when B does not occur, then A did not occur either [Christoforides, Spanoudis, & Demetriou, 2016]. Thus, children grasp the (biconditional) relation between modus ponens and modus tollens (i.e., if p then q; q then p; not q then not p). Therefore, awareness of underlying relations allows moving across rules that may then guide executive control and reasoning.

Overall, in this period, relational definitions become increasingly dominant over particular representations or episodic relations, yielding generic concepts supervening earlier global representations, such as natural kinds (e.g., animate vs. inanimate, etc.). Thus, the dimensions or rules defining semantic blocks can systematically be aligned with each other. In categorical thought, two independent dimensions (life/living vs. non-living beings, and movement/moving on earth and flying) can be operated on so that all possible cross-classifications and their logical relations can be grasped (e.g., class inclusion: animals are more than birds). In quantitative reasoning, children start to handle proportional relations (e.g., 2/4 and 4/8). This is also reflected in children's facility in handling analogies and metaphors (e.g., "teachers are for schools what parents are for families"). Emergent logical necessity in this phase is a strong sign of this awareness (e.g., “All balls in the box are red, so the next to be drawn out MUST be red” [Miller, Custer, & Nassau, 2000]).

Principle-Based Thought. At 11–13 years, adolescents form accurate maps of mental functions and of their own strengths, they evaluate their own performance on cognitive tasks, they cognize the constraints of different inferential processes, and they can ground inference on truth and validity rules [Demetriou et al., 2017; Demetriou & Kazi, 2006; Makris et al., 2017]. As a result, mental focus shifts from representations and rules to relations between underlying rules connecting mental spaces, encoding them into generic principles. For instance, they can now solve the most difficult Raven matrices that require deciphering multiple dimensions and integrating them into complementary principles. Thus, emerging principles interconnecting rules allow cognizing the constraints of different inferential processes. For instance, they explicitly understand that accepting certain conditions (e.g., birds fly; elephants are birds) imposes constraints on inference (i.e., elephants fly), even if a statement is admittedly wrong (elephants are not birds). Formally speaking, these constraints are rules of truth yielding consistency in reasoning. This is obvious in all domains. For example, in the domain of quantitative thought, they reduce the various instantiations of the mental number line into an algebraic conception of number as a variable that can take any value (e.g., they can understand “$L + M + N = L + P + N$” when $M = P$). As a result, number can be explored as such, defined in alternative ways (e.g., natural, real, imaginary number, etc.) [Dehaene, 2011]. In the first phase, conceptual spaces may be explored as such in reference to one or more alternative principles. The hypotheticodeductive stance of the young adolescent reflects this possibility.

By the age of 13–14 years, “reasoners have a meta-representation of logical validity that can be used to inform them of the accuracy of their logical deductions, at least when reasoning about abstract materials” [Markovits, Thomson, & Brisson, 2015, p. 691]. Adolescents become aware of the logical constraints underlying different types of relations. This is expressed in their ability to discern when an argument is logically insolvable, as in the so-called fallacies of affirming the consequent or denying the antecedent. For instance, they understand that no conclusion can be drawn from a modus ponens-like argument where the second proposition is affirmed. Formally, adolescents understand that accepting that “If A then B” does not allow drawing any conclusion about A if only knowing that B occurred or drawing any conclusion about B if only knowing that A did not occur, because B may be caused by something other than A. This is so because complementary representations can be aligned along a validity principle and evaluated for consistency. Later, principled thought culminates into a systemic approach allowing the alignment of multiple principles (e.g., truth-validity-morality) and their reduction into grand frames, such as an overarching life orientation [Demetriou & Bakracevic, 2009]. At this phase, however rare it is, systems may be aligned with each other. The use of mathematics for the sake of problem solving in other sciences is an example of systemic alignment.

In this second phase, awareness of mental processes develops into a detailed differentiation between mental functions, such as attention, memory, and reasoning, and their association with relevant processes, such as choice and inhibition, recall and association, and inductive and deductive inference, for each of these three functions, respectively. Thus, adolescents become increasingly able to associate a problem with relevant mental processes. For instance, if one needs to test a hypothesis, isolation of variables is the process needed; if one needs to fix objects in the boot of a car, mental rotation is the process needed [Demetriou and Spanoudis, 2018; Makris et al, 2017]. Thus, 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. Control also becomes differentiated in this phase. The system of principles is used to co-activate conceptual spaces, such as beliefs and knowledge about study or professional options and evaluate them against each other in order to form long-term life plans [Demetriou & Bakracevic, 2009; Moshman, 2011].

State of the Art about Developmental g. The state of the art conclusion regarding development may be as follows: the constitutional processes of g are always present in development. However, their relative contribution varies, suggesting that developmental g differs from its mature state in the adult. Overall, the contribution of attention control and flexibility diminishes but the contribution of working memory, cognizance, and inference increases with age as the first automate and the second are increasingly needed to handle the increasing multiplicity of the representations mediating between the individual and the world.

Mapping Changing Relations between Processes of Developmental g

The developmental sequences outlined above suggest that patterns of change vary with process and phase. This may reflect two related but distinct types of processes. On the one hand, they may indicate that the strength of relations between specific abilities and general ability varies with phase, depending upon the developmental priorities in the construction of general ability in each phase. On the other hand, change in developmental patterns may mark when a new ability emerges and when it reaches a level of relative stability. In turn, changes in these patterns may indicate when this ability intertwines with g in the phase concerned. For instance, change in a particular mental process M may accelerate after g reaches a particular level (partly associated with age) to match this level, and it decelerates as it approaches this level. Therefore, these changes relate to a question that has been debated for decades in both psychometric and developmental psychology: are mental processes integrated or differentiated from each other with increasing ability or growth?

Resolving the Differentiation Dispute

Answers to this question are disputed across and within disciplines. Psychometric theory and developmental theory agree that mental possibilities change with growth. Theories also agree that individuals differ in their rate of enhancement or final attainment. IQ in psychometric theory recognizes that chronological and mental age may not coincide and specifies how they relate with reference to a given individual's age group. Developmental theory considers stages as ideal epistemic states corresponding to successive age periods and recognizes that rate of progression along stage sequences or final stage attainment may differ across individuals.

Several mechanisms were invoked to account for developmental progression and ensuing enhancement of mental ability with age. The twin mechanism of integration/differentiation of mental processes is a major mechanism of development. Psychometric theory postulates that increasing g allows increasing differentiation of cognitive abilities, because increased ability may be invested into some domains more than in others, causing domains to differentiate. This is Spearman's law of diminishing returns for age [Jensen, 1998; Spearman, 1927]. The developmental adaptation of Spearman's differentiation hypothesis would assume that abilities differentiate with growth because g increases with development. Cognitive developmental theories postulate that increasing ability comes from increasing integration of mental processes [Case, 1985; Piaget, 1970]. Piaget's equilibration is a developmental mechanism generating increasingly integrated mental structures. Tuning with the environment indicates some kind of differentiation because abilities may efficiently differentiate concepts according to the specificities of particular situations and operate accordingly.

Technically, a decrease in correlations between abilities with increasing g was considered as evidence favouring differentiation. In terms of factor analysis, the equivalent would be an increase in the number of factors needed to account for performance of high g individuals as compared to lower g individuals. According to Detterman's [1987] theory of mental retardation, the malfunctioning of central mechanisms in individuals with low intelligence causes homogeneously lower performance across abilities: hence higher correlations and stronger g. Some studies did find the expected pattern of decreasing correlations or increasing number of factors with increasing age [e.g., Deary et al., 1996; Reynolds, 2013].

Along this line, one of our studies examined participants from 4 to 16 years of age on several measures of processing speed and attention control, executive, phonological and visual working memory, two domains of reasoning, quantitative and spatial, and deductive and inductive reasoning [Demetriou et al., 2013]. We used confirmatory factor analysis to examine the optimum number of factors needed to account for performance in three age phases: 4–7, 6–11, and 10–16 years. We found that in the representational cycle, from 4 to 7 years, one single factor was sufficient to account for performance on working memory and reasoning tasks. This factor was related to processes indicating processing efficiency measures. In the next cycle, from 6 to 11 years, two interrelated factors, one for working memory and one for reasoning, were needed to account for performance, indicating differentiation between representational and inferential processes. Both of these factors were related to reaction time measures of speed and attention control reflecting mental efficiency. Finally, a three-level hierarchical model accounted for performance in the third cycle, from 11 to 16 years. In this model, three factors emerged: mental efficiency, working memory, and reasoning. Mental efficiency resided at the fundamental level, sending influences to working memory which resided at an interfacing level, and thus sending effects to the reasoning factor which resided at the top.

However, other researchers did not find any increase in the number of factors with development [Carroll, 1993; Hartman, 2006]. Using methods allowing separation of ability from age, several researchers found clear evidence in favour of ability differentiation but not in favour of age differentiation [Tucker-Drob, 2009]. That is, differentiation occurs with increasing ability regardless of age. Facon [2006] found that ability differentiation is age dependent, showing up in late childhood. Obviously, these findings align with the distinction between mental and chronological age, implying that differentiation of abilities occurs as a function of mental rather than chronological age. Our theory offers a reason for this state of affairs. Specifically, this theory suggests that differentiation may vary according to developmental phase and

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the dominant representational characteristics of g. That is, both differentiation and strengthening of relations between specific mental processes and g are possible. However, these changes in the relations between g and specific abilities depend upon the developmental priorities dominating in the formation of g in each phase. Specifically, the primary developmental task in the cycle of realistic representational thought is representational control. This may express itself in several forms, such as control of attention focus and control of shifting between stimuli or responses. The primary developmental task of the next cycle of rule-based thought is inferential control. That is, the command of the inferential process so that it can fill in gaps of information systematically. This is primarily expressed through changes in awareness of the inferential processes itself and also through improvements in the application of the inferential processes as implicated in analogical and Raven-like tasks. The primary developmental task in the cycle of principle-based thought is command of cognizance and related rules so as to ensure truth and validity of inference. This is primarily expressed through accuracy in self-representation and self-evaluation and in explicit matching of specific processes with specific problems. Each of these processes ought to spurt in the developmental phase concerned (i.e., 4–6, 6–8, and 11–13 years, respectively), marking the major acquisition of g in each phase.

Mapping Changes in Structural Relations and Developmental Patterns

We employed two complementary methods to explore these phenomena: the first method, recently proposed by Tucker-Drob [2009], is appropriate to capture changes in the structural relations between specific processes and general ability. This is a structural equation model specifying how each specific ability varies with increases with g and progression of age in an age period of interest. Thus, it allows testing the possible differentiation of abilities with increasing g or age. Technical manipulations in building the model allow to dissociate the possible influence of increases in g from the possible influence of age progression, showing whether changes in a specific ability tend to become increasingly (a) intertwined with changes in g, (b) differentiated from it, (c) or staying the same [see Demetriou et al., 2017; Demetriou & Spanoudis, 2018].

The second method focuses on possible changes in developmental patterns as a function of developmental g, which is the product of g and age. This is segmented linear regression, a version of linear regression, which specifies how the rate of change in a specific process of interest varies at different regions of developmental g. In each case, we compared a linear model assuming that increases in the specific ability of interest are proportional to increases in developmental g with segmented models assuming that the degree of change in a specific ability is not the same in different regions of developmental g. For instance, change in an ability is faster at the lower levels of developmental g, decelerating at its higher levels. This appears as growth lines with different slopes [Crawley, 2007].

The two methods together can show how changes in developmental patterns of specific abilities reflect changes in the formation of general ability. We tested the two models in several studies to highlight how various specific processes interact with general developmental ability to produce the patterns shown in Figure 4 [Demetriou et al., 2017]. The message of the studies presented is clear and simple. Differentiation

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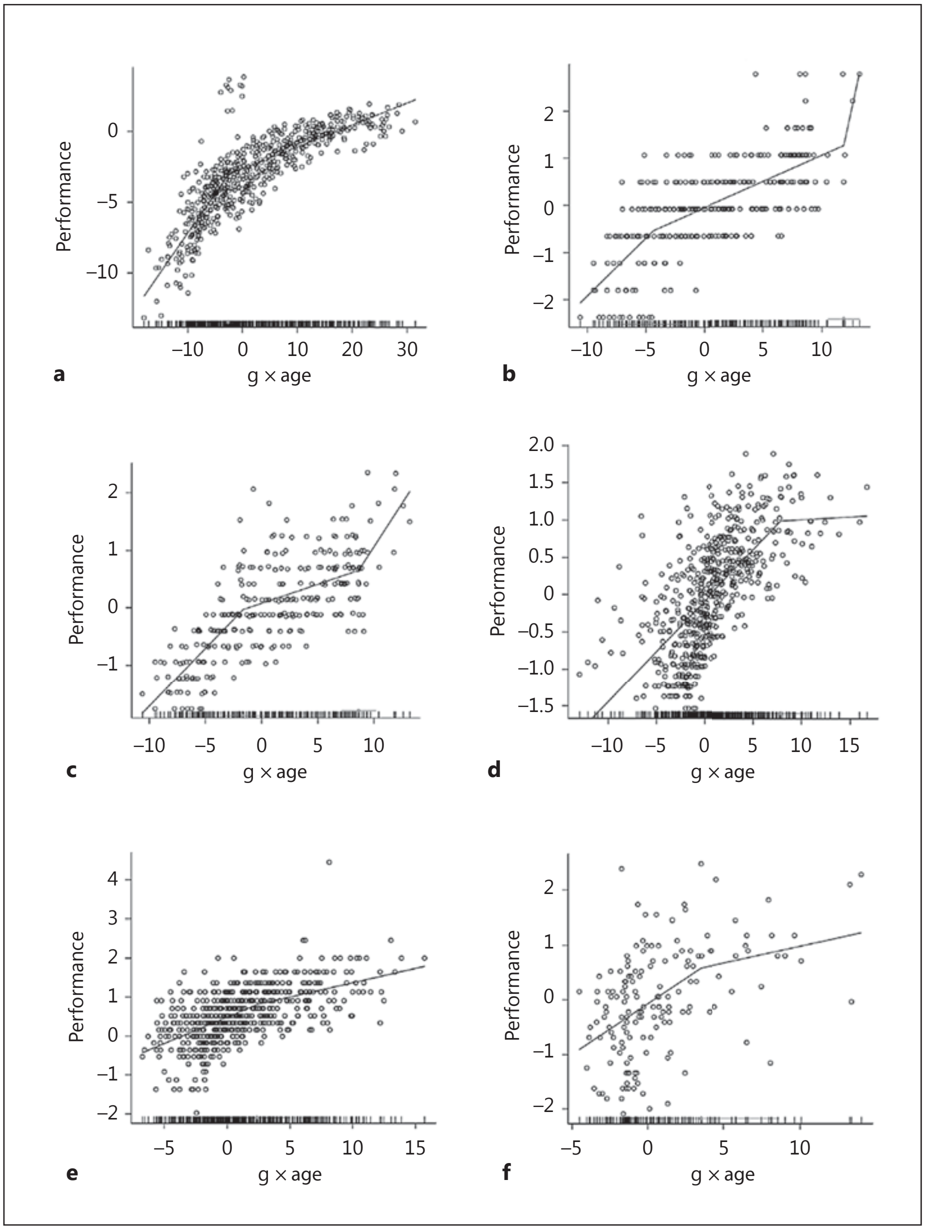

Fig. 4. Relations between specific mental processes and developmental g (g × age). Segmented models of the relations between specific mental processes and developmental g (g × age). **a** Attention control from 4 to 17 years. **b** Inductive reasoning from 7 to 11 years. **c** Inferential awareness from 4 to 10 years. **d** Principle-based reasoning from 12 to 20 years. **e** Self-evaluation accuracy of principle-based problem solving from 12 to 20 years. **f** Awareness of domain-domain-specific principle-based processes from 12 to 17 years.

from and intertwining of specific processes with g is a developmental rather than an individual differences phenomenon, varying with developmental cycle and phase. New acquisitions in each cycle become increasingly integrated into g, infusing g with their properties but they may differentiate later on.

Changes in control of attentional focus strongly intertwine with g in the cycle of reality-based representations, especially in the 4- to 6-year phase (Fig. 4a). Awareness of the perceptual origins of knowledge also contributes to g in this phase. In the next cycle of rule-based thought, attention control is left behind and inductive reasoning dominates as a contributor to g. That is, in this phase inductive reasoning intertwines increasingly with g (Fig. 4b). Awareness still actively infuses g with its properties but it mutates from perceptual to the inferential aspects of representations (Fig. 4c). In the next cycle inductive reasoning recedes, and principle-based deductive reasoning, in its most advanced versions of conditional reasoning, dominates as the major source of infusion of new properties into g (Fig. 4d). In this cycle, awareness of specific mental processes activated in each domain (Fig. 4e) and accurate self-evaluation of performance continue to be part of g remorphing. Awareness in this cycle comes as a refined theory of mental processes tuned to one's own personal strengths and weaknesses. Thus, it seems that incipient grasp of principled thought at 11–12 years (Fig. 4e) is intertwined with awareness about it before it is consolidated by the end of this cycle. At 14 years adolescents also start to precisely match specific domains of thought, such as causal, spatial, and mathematical reasoning, with specific processes, such as isolation of variables, mental rotation, and proportional reasoning, respectively; also, they differentiate between the mental effort imposed by different processes based on their procedural complexity (Fig. 4f) [Demetriou et al., 2017; Demetriou & Spanoudis, 2018].

The findings above give an impression that intertwining dominates over differentiation. However, this impression is not accurate. Differentiation is present but it recycles with intertwining. Processes that intertwined with g when they were integrated into it differentiate from g at a subsequent cycle, when their relations with g get loose, because they are already under command. Counting the number of factors is a different matter. It is indeed the case that with growth more factors are needed to account for performance. Attention control is a sweeping force in the reality-based representations cycle. Lapses in it cause functioning in all other domains to falter. Later, in the rule-based cycle, representational processes split from inferential processes in g. As a result, lapses in one can be compensated by contributions from the other, as when lags in memory can be filled in by inference. Thus, decisions are more flexible because there is a system that can make intentional choices. In the next cycle of principle-based thought this is further differentiated in reference to personally tailored values and preferences. All in all, psychometric differentiation comes as a result of a developmental process underlying the transformation of g along its various constituents, where their relative contribution varies.

Structural Relations within Phases

The patterns above suggest that the relations between various aspects of executive control, on the one hand, and reasoning, on the other hand, vary with age. To further explore these relations, we tested a rather simple structural equations model on each age phase separately (i.e., 4–6, 7–8, 9–10, 11–13, and 14–16 years of age). This model explored the relations between speed, attention control, and working memory, on the one hand, and reasoning, on the other hand. Thus, it can show how the relations between Gf and various aspects of processing efficiency vary with developmental phase, if at all. It is emphasized that these relations were tested by modelling the results of a large number of published studies where speed, working memory, and general intelligence were measured in each of the age phases above [Demetriou et al., 2013, 2014].

A consistent pattern of relations was found across studies. Specifically, in the early phase of each cycle the relations between speed or attention control and reasoning were high (ranging between 0.6 and 0.8) and the working memory-reasoning relations were low or moderate (approx. 0.2 to 0.4). This relation was inverted in the second phase of each cycle, when the speed-reasoning relations dropped drastically (approx. 0.2–0.3) and the working memory-reasoning relations rose drastically (always aprrox. 0.7). At the beginning of cycles, processing speed on tasks requiring attention may increase for several reasons. For instance, individuals master the new executive program increasingly automating its handling. For instance, in the first phase of realistic representations children become increasingly able to focus on representations, select those which are relevant, and inhibit irrelevant ones. At the beginning of rule-based representations, children become increasingly able to focus on underlying relations and encode them into rules. In short, command of the new control program and related representational unit improves fast at the beginning of cycles, and thinking in terms of it proliferates to new content. Later in the cycle, when the control program is transcribed in different conceptual domains and networks of relations between representations are worked out, working memory is a better index because alignment and interlinking of representations both requires and facilitates working memory.

Specifying the Mediating Role of Cognizance across Phases

We conducted several studies to test how cognizance mediates between various aspects of executive control, such as attention control and working memory, and various aspects of reasoning, such as deductive, inductive, and spatial reasoning. Both, bottom-up mediation and top-down mediation were examined. The overall model tested on these studies is shown in Figure 5. In the bottom-up model the executive factors (i.e., speed, attention control, and working memory) were taken as the background factors which were directly regressed on age. Cognizance was regressed on the executive factors. The reasoning factors (i.e., inductive, deductive, and spatial reasoning) were regressed on a common reasoning factor which, in psychometric terms, stands for Gf. This Gf factor was regressed on cognizance, which was thereby upgraded into a mediating factor carrying the effects of the executive factors to the reasoning factors. In the top-down model the reasoning factors were taken as the background factors which were directly regressed on age. The executive factors were regressed on a common factor that stands for executive control. This executive control factor was regressed on the cognizance factor that carries the effects of the reasoning factors onto the executive factors.

We showed that in the phase of 4–6 years cognizance is much more powerful as a bottom-up rather than as a top-down mediator for children up to 7 years of age.

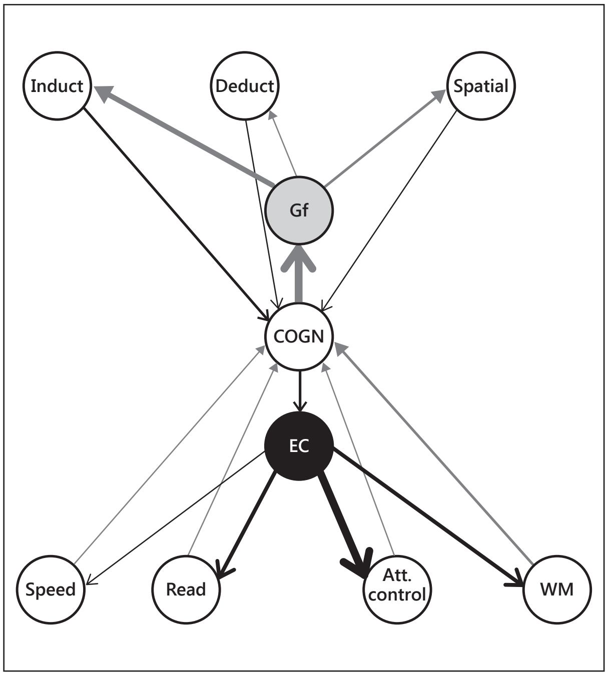

Fig. 5. Mediation models showing how cognizance (COGN) mediates between executive control (EC) and fluid intelligence (Gf). WM, working memory.

That is, the various executive functions (working memory and attention control) do contribute to the emergence of awareness, which is then used in handling reasoning. Therefore, executive control systematically contributes to the emergence of perceptual awareness about mental processes. That is, that knowledge and mental states emerge from perception (seeing, hearing, etc.). This awareness, when acquired, is carried up, enabling children to put their processing resources (i.e., focusing, flexibility, and representing in working memory) in the service of information integration and reasoning. Finally, it is noted that these effects are not exerted uniformly on all reasoning domains. They influence inductive reasoning more than deductive and spatial reasoning. Moreover, this effect was primarily mediated by working memory [Spanoudis et al., 2015].

The top-down model showed that reasoning also contributes to the emergence of awareness. However, this awareness is weakly carried down to executive processes in this age phase and not for all children. This influence occurs only for children who are already strong in their command of attention control. Specifically, we found that cognizance emerging from reasoning affected executive processes in children who were already high in attention control but not in children who were low in attention control. Also, in this top-down model cognizance was affected by deductive reasoning more than by inductive and spatial reasoning, probably because it is more demanding in the mental manipulations involved.

Another study sought to further explore the mediating role of cognizance by zooming in on the processes involved in it. This study involved 344 children about equally drawn from each of the age years 4–10. Specifically, this study involved speed, attention control, conceptual control, and working memory measures similar to those used in the study above. With respect to reasoning, this study involved a Raven-like test developed for the present purposes. This test involved tasks addressed to three levels of complexity, which are known to be mastered at 5–6 years, 7–8 years, and 9–11 years, respectively. Several tasks addressed awareness of perception and inference as sources of knowledge. In the perceptual awareness tasks children saw a figure placing objects in same-colour boxes according to their colour and heard the figure describing what she did before. Children were then asked to specify the location of objects based on what they saw and heard before. In the inferential awareness tasks, children saw the same figure hiding objects in same-colour boxes but they were subsequently asked to locate objects of a different colour not shown before. Thus, this condition addressed awareness of inductive extrapolation as a source of knowledge. That is, that this not-seen-before object must be in a same-colour box, given that the figure is placing objects in same-colour boxes [for details, see Demetriou & Spanoudis, 2018; Spanoudis et al., 2015].

Bottom-up and top-down mediation of cognizance between processing efficiency and reasoning was modelled in the fashion described above for children 4–6 and 7–10 years old. In the bottom-up model, in the younger age group, reasoning was significantly related to perceptual awareness but not to inferential awareness. In this group, perceptual awareness carried significant but weak effects from attention control to reasoning. In the older age group, reasoning was negatively related to perceptual awareness, obviously reflecting the fact that perceptual awareness had approached ceiling in this age group. However, reasoning was positively related to inferential awareness. In this group inferential awareness carried effects from speed and attention control to reasoning. In the top-down model, in the younger age group, the effect of perceptual awareness on the general executive control factor was strong but the effect of inferential awareness was low. Notably, the top-down effects of reasoning on perceptual and inferential awareness were very strong, carrying significant effects on speed, attention control, flexibility, and working memory. In the older age group, there was no effect of perceptual awareness on efficiency suggesting that the top-down effects of reasoning were weak. Finally, another study sought to specify the mediating role of cognizance from 9 to 15 years of age [Makris et al., 2017]. In this study the mediatory influence of attention control and shifting reached ceiling by the age of 13 years and dropped thereafter. However, the executive processes-cognizance-g relation was strong throughout this age period, suggesting that by the middle of rule-based thought cognizance exerts a strong mediatory role in the relations between executive processes and reasoning or language.

The studies presented in this section revealed three tendencies concerning the role of cognizance. First, its mediation between executive and reasoning processes is cycle-specific, depending on the representational state of g. That is, it is exerted through the processes underlying the management of representation in each cycle, such as the perception-based aspects of representation in the representational cycle, rule-based inferential processes in the rule-based cycle, and abstract semantic processes in the principle-based cycle. Second, bottom-up mediation is stronger than top-down mediation. In fact, top-down mediation is not attained before the second phase of rule-based thought and it is more likely to be attained by individuals who are high in both executive processes and inferential processes demanding reflection, such as deductive reasoning. Notably, this type of mediation is difficult to scan in adolescence because various aspects of attention control and flexibility reach ceiling. Third, awareness of similarities and differences between cognitive processes and their relative cognitive demands is more demanding than global awareness of the role of different modalities in the origins of knowledge and understanding. As a result, this more refined aspect of cognizance is more sensitive in differentiating between bottom-up and top-down mediation. Thus, top-down mediation is present only in individuals who are very efficient in the control of attentional processes.

State of the Art about Relations between Processes. The research presented in this part suggests an intriguing integration of the psychometric, the cognitive, and the developmental approach to intelligence. Specifically, *changes in the relations between the ever present inferential processes in g and processing and representational processes operate as markers of developmental changes in inferential processes.* Specifically, changes in attention control and related speed measures mark the beginning of cycles. Changes in working memory mark the end of cycles. Changes in mental flexibility in shifting across representations and explicit cognizance about them occur in the middle of cycles. Changes in reasoning show up after these middle transition points reflecting the progression attained in the alignment and integration of representations in a given phase. Thus, integration in and differentiation of individual processes in g reflect g's constitutional needs in each cycle.

Learning: Can Intelligence Be Increased?

Our causal models of the relations between processes bear implications for the transfer of learning across processes. For instance, in the CHC 3-stratum model of intelligence, causal effects run top-down from g to broad abilities to specialized skills. Therefore, if there is any reality to this model, training second- or third-stratum abilities, such as processing speed or working memory, would not transfer to g-specific abilities, such as fluid intelligence or generalize to other abilities. However, training these g-specific abilities would transfer to second- or third-stratum abilities, such as working memory or attention control [Protzko, 2015]. There has been extensive research examining transfer effects along all directions. The pattern is clear by now and in agreement with this assumption: studies attempting to change general intelligence by training working memory, speed, or executive control did succeed with their chosen factor. However, they did not appreciably enhance g [Melby-Lervag, Redick, & Hulme, 2016; Sala & Gobet, 2017; Protzko, 2015; Shipstead, Redick, & Engle, 2012].

There is a special class of processes concerned with the transfer of learning: mediating processes, such as cognizance, if directly affected by training, would normally spread the effect both ways, top-down and bottom-up. There is some research showing that training reflection as such does generalize to executive control and cognitive processes such as sorting [Espinet, Anderson, & Zelazo, 2013; Zelazo, 2015].

Research Manipulating Cognizance

We conducted several studies to examine whether changing relational thought and cognizance would change intelligence. One of these studies examined whether training inductive reasoning in mathematics and related awareness would improve performance in several aspects of mathematics and if this would generalize to other aspects of intelligence [Papageorgiou, Christou, Spanoudis, & Demetriou, 2016]. This study involved 11-year-old children. Half of them were randomly assigned to the training group, and the rest were used as controls. All children were pretested on various aspects of attention control, working memory, and reasoning (deductive, analogical, spatial, causal-scientific, and mathematical). Children in the training group were trained to use relational thought in the domain of mathematics. Children were instructed to identify the dimensions underlying the various mathematical reasoning tasks involving number series in various patterns (e.g., double, triple, half, one fourth) and mathematical analogies, explicitly conceive of their similarities and differences, group them according to organizational rules, and build the problem-solving skills associated with each. Thus, they were required to explicitly metarepresent both problem structures and processes as well as their associations. The emphasis was on formative concepts like “attributes,” “relations,” “similarity,” “dissimilarity or difference,” and their instantiation in the various problem types.

The change in the domain of mathematical reasoning was considerable soon after the end of the intervention (effect size = 0.38), although not all of it was sustainable about 6 months later (effect size = 0.20). However, the gains did transfer to domain-free analogical reasoning tasks (effect size = 0.20) and, to a lesser extent, to other domains, such as deductive reasoning (effect size = 0.12). Gains in deductive reasoning were stable from second to third testing (effect size = 0.13), when they dropped below significance in other domains implying transcription of gains into more formal inferential processes. Also, there was a strong effect on working memory (0.93) and a less strong but significant effect on Gf (0.38) and attention control (0.10), which were preserved at a delayed posttest. Obviously, these effects indicate that cognizance mediated in the transfer of gains in relational thought to processes residing in the executive control level.

Christoforides et al. [2016] focused on cognizance of reasoning schemes. Specifically, this study trained 8- and 11-year-old children, split between a limited instruction and a full instruction group, to become aware of the logical characteristics of the four basic logical schemes of conditional reasoning: modus ponens, modus tollens, affirming the consequent, and denying the antecedent; also we trained children to build and mentally process mental models appropriate for each scheme and explicitly represent their relations (e.g., that affirming the consequent is not the opposite of modus ponens and denying the antecedent is not the opposite of modus tollens). The aim was to examine whether enhancing cognizance via conscious inferential activity about these schemes and processes would result in a transition from rule-based to principle-based deductive reasoning. At the same time we investigated whether possible progress depends on attention control and working memory. The limited instruction group learned the notion of logical contradiction and the logical structure of the schemes involved. The full instruction group learned, additionally, to adopt an analytical approach to logical arguments, in contrast to their “everyday” usage in language, differentiate between the stated and the possibly implied meaning of propositions, recognize logical contradiction and truth in propositions and reality, and grasp the notions of logical necessity and sufficiency.

In terms of spontaneous developmental time, this short training program pulled children up by almost a full developmental phase, especially in the full instruction group: overall effect size for reasoning and awareness was 0.72 and 0.36 and 0.92 and

0.37 in the limited and the full instruction group, respectively. That is, trained third-graders handled problems at the level of principle-based reasoning *if aided by context*; sixth-graders moved to this level regardless of content and context. Specifically, this intervention enabled both age groups to master the fallacies of affirming the consequent (knowing that when A occurs B also does not allow any inference about A when knowing that B occurred) and denying the antecedent (under this condition, knowing that A did not occur does not allow any inference about B). The key to this success was awareness of the inferential identity of each scheme and the principle of logical consistency. The limited instruction group trained in these two aspects of inferential awareness performed close to the full instruction group. Overall, awareness almost fully mediated the influence of training on deductive inference. However, awareness as such improved significantly only in the full instruction group and was highly dependent on attention control and working memory. In short, third-graders grasped the logical principles implicitly; sixth-graders grasped the principles explicitly and performed accordingly. These findings provided an experimental demonstration of the mediation models above that a top-down design involving children thinking about reasoning itself affects cognizance which then transfers to various tasks.

Large-Scale Acceleration of Cognitive Development

Shayer and Adey [2002] developed a complete intervention program conceived as teaching art integrating Piaget, Vygotsky, and Feuerstein. The aim was to accelerate cognitive development along Piagetian stages with a focus on science and mathematics concepts. These were related to the Piagetian formal operational schemata, such as combinatorial thought, control of variables, proportionality, and equilibrium of systems. Vygotsky offered two important notions: the *zone of proximal developmental* and social interaction with peers and adults. Vygotsky suggests that negotiating one's understanding with others helps one move through the zone of proximal developmental and reach the higher levels of a concept. Mechanisms such as internal speech help one to reflect and internalize the other's perspective, thereby enhancing one's understanding. Feuerstein offers the recognition of the fact that classrooms involve students of varying levels, and this is a reality to capitalize on for the benefit of all.

The intervention program evolves along a series of training steps. At the beginning, students are introduced to the subject of investigation and learn the technical vocabulary needed. Then they work on examples varying on a series levels so that all may, from their present zone of proximal developmental level, go at least one step higher. This design principle is called *cognitive conflict* and conflict resolution through reflection on what has been achieved. Then they work on the task in small groups of three or four until they have gone as far as they can, eventually reporting to the whole class. The teacher's aim of this intervention may appear top-down, but it is bottom-up in terms of its collaborative learning practice. Since it is typically used in the first 2 years of secondary school (12–14), the intention is to promote principle-based thought, which was spontaneously achieved at a full level by only 13% at 16 in 1976 and by only 2% in 2007, indicating a decrease in formal thought [Shayer, Ginsburg, & Coe, 2009].

The main findings are summarized in Figure 6. It can be seen that there is improvement because of the intervention in children of all levels. In terms of Piaget's

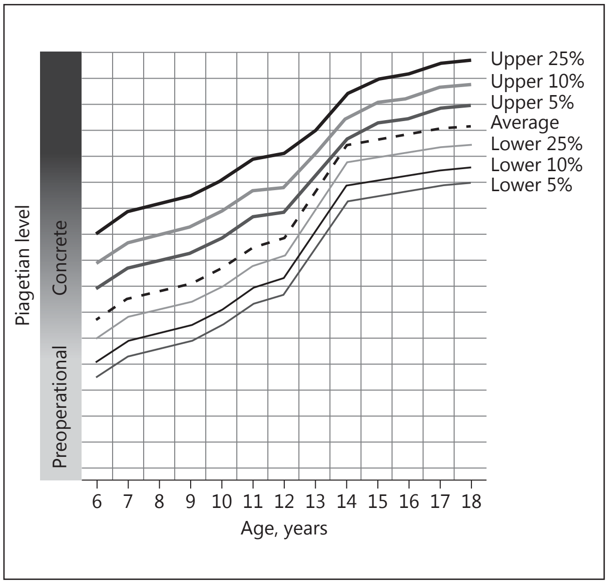

Fig. 6. Distribution of cognitive developmental levels in the general population and cognitive change as a result of intervention, which lasted from 12 to 14 years of age (based on CSMS survey data of 1975–1977).

stages, on average, trained children moved from late concrete thinking to early formal thinking. However, on the one hand, only children operating before training at late concrete thought moved to any level of formal thought and only those operating at transitional levels between concrete and formal thought moved to late formal thought. On the other hand, those operating on preoperational or early concrete thought moved up to late concrete thought but not beyond. It was found, 3 years after the intervention when the students took their national exams at 16, that the 11 schools involved in the study significantly outperformed control schools with effect sizes of 0.60 for science, 0.50 for mathematics, and 0.57 for English. The fact that the effects were nearly as large for English as in science shows that it was the pupils' general thinking ability that was affected, as was intended.

State of the Art about Learning. All of the above studies used a top-down design addressing relational processes involved in inference and reasoning or cognizance itself. These studies showed that intelligence can be increased and increases may transfer top-down to executive control and working memory. However, this requires focusing on relational thought and awareness of processes pertinent for a specific developmental phase with phase sensitive methods.

Discussion: Implications for Cognitive, Developmental, and Educational Science

This section focuses on three themes. First, we discuss the implications of our findings for the nature of g, outlining its main dimensions and properties. Second, we focus on development, pointing to aspects of g staying stable and aspects changing in development. Finally, we discuss the implications of these findings for long-standing questions in psychometric, developmental, and cognitive science, showing that we answer unanswered questions, integrating constructs from earlier theories that stood up against the test of time with new constructs accommodating phenomena that were overlooked by earlier theories.

Redefining g

The first part concluded that g is a function of executive control, flexibility, working memory, cognizance, and inference. That is, g is neither defined just by a single component (i.e., executive control) shared by all inferential processes [Kovacs & Conway, 2016] nor just an interactive product of specialized processes, which do not have an identity of their own [van der Maas et al., 2006]. Obviously, these processes do interact; however, interactions are orchestrated by a pivotal mechanism holding them together.

To integrate the cognitive, the psychometric, and the developmental tradition, we need a mechanism that would do justice to the procedural, the representational, and the generative aspects of understanding at the same time. This mechanism would capture the interactive aspect of the five processes comprising g. We suggest that this mechanism involves three interdependent processes [Demetriou et al., 2013]: (a) abstraction; (b) representational alignment, and (c) cognizance – the AACog mechanism. Abstraction spots or induces similarities between patterns of information. Alignment is a "search, vary, and compare" mechanism interlinking stimuli and/or representations together according to current goals; perceived current similarity and semantic relevance provide direction and criteria for alignment. Thus, alignment is an executive mechanism of representational integration, involving shifting between representations or shifting between representations and responses [Miyake & Friedman, 2012]. It feeds inferential processes with raw material that may lead to inductions and deductions according to specific binding and evaluation rules activated at a given moment [Demetriou et al., 2013]. Cognizance has already been defined above as self-monitoring, awareness, and reflection on mental processes and metarepresentation encoding the products of abstractions and alignments into new representations. Thus, cognizance is a unifying force. It may arise as a side effect of cognitive functioning whenever abstraction and alignment fail. Needing to choose between stimuli or possible actions turns the "mind's eye" to them thereby bringing them into the focus of awareness. So defined, cognizance allows feedback loops where cycles of abstraction and alignment can become the object of further abstraction and alignment that are represented into new mental units.

One might object that the explanatory function of cognizance collapses into a homunculus, in that we relegate explanation of mental causality at one level to a construct at another level, which still needs to be explained. However, this is not the case because the explanatory power of cognizance emerges from its unsupervised regulatory possibilities, in the fashion awareness and metacognitive regulation emerge in the brain or learning emerges in machine learning systems. According to recent models, abstraction and awareness emerge from layers of superimposed neuronal networks (real in the brain or artificial in machine learning) interacting bottom-up and top-down [Haier, 2017; Taylor, Hoobs, Burroni, & Siegelmann, 2015]. In these hierarchies, some object characteristic (e.g., physical characteristics such as colour or shape) and processes (such as vision or sorting) at lower levels are projected onto higher levels. In a Gödelian sense, lower level properties and processes may become known at higher levels, and they are accessible from there in order to be modified, if they are not consistent, tuned, or integrated for economy, or selected, if more than one may be applied. No homunculus is around. Explanation lies in the corrective and interactionist possibilities of layers interacting with each other, each directly evaluated vis-à-vis feedback from the environment. In line with this interpretation, several studies suggest that even when the search for and the abstraction of rules are unconscious they generate experiences that are registered and exert metacognitive influences on further processing and reasoning [Mealor & Dienes, 2013; Scott, Dienes, Barrett, Bor, & Seth, 2014]. In psychological terms, these superimposed networks have an equivalent in both the hierarchical models of cognitive process built by psychologists, the subjective models coming out of modelling self-evaluation and self-awareness data [Demetriou & Kazi, 2006; Makris et al., 2017], and the causal effect of cognizance and reflection training on other mental functions [Christoforides et al., 2016; Espinet et al., 2013; Zelazo, 2015].

In conclusion, AACog integrates Spearman's [1927] eduction of relations (abstraction) and correlates (alignment) underlying g, Piaget's reflective abstraction and equilibration, and reasoning and consciousness that dominated in post-Piagetian developmental research. Modern as it is, this approach reminds us of Kant's conception of intelligence. Kant, in the middle 18th century, believed that intelligence exists only by virtue of awareness of the very ability to combine representations for the sake of understanding and judgement: "I exist as an intelligence, which is conscious of its power of combination" [Kitcher, 1999, p. 375]. Obviously, a large knowledge base, crystalized intelligence in psychometric terms, is an advantage to the thinker because it enhances the options the thinker may choose from in aligning, abstracting, metarepresenting and crafting solutions. This mechanism must be operational in its entirety by the end of the first year of life [Demetriou and Spanoudis, 2018].

One might ask here about domains: What do the present findings imply about the status of special domains of understanding and problem solving, such as causal and mathematical thought? One answer resides in the models summarized in Figure 1. We are reminded that up to 98% of the variance in many reasoning and language domains was accounted for by g. Formally, $G_{\text{domain}} \approx g$. However unexpected it was, this finding strongly suggests that mastering the mental operations and skills related to any domain within any of the developmental cycles specified here is commensurate to the state of g. That is, in each phase, g may be translated into domain-specific operations with learning.

The discussion here bears implications for the CHC model outlined in the introduction. Specifically, the definition of g proposed here suggests that the CHC model mixes up proper conceptual/problem-solving domains, such as spatial reasoning and language, with executive control domains, such attention control, or representational domains, such as memory. The present discussion suggests that we should keep conceptual domains separate from efficiency or representational domains. Conceptual domains are "languages" to be learned. Efficiency and representational domains set processing constraints and provide the general syntactic and compositionality codes to be used for learning the special languages.

Redefining Developmental g

It is important to recognize that psychometric g is meaningless if dissociated from developmental g. In a sense, any individual's intelligence is what this individual has constructed by a certain age. For children, there still are prospects for further development. For adults, intelligence reflects how far one has gone across developmental g. Although the processes above are always involved in g, their relative contribution and relations change with age. Early in development, in the episodic cycle, awareness of actions and action-object relations is explicit but awareness of intervening representations is implicit. Revisiting episodic blocks allows the infant to abstract action patterns, interrelate them, and represent them in language or other representations, generating the realistic representations of the next phase. However, the episodic mind is captive of environmental variation, guided by it as much as it errs because of it.

Later, in early childhood, at 3–4 years, children become explicitly aware of representations but not of underlying mental processes. Thus, in the first phase of the representational cycle, mastering attention control and inhibition dominates: children focus on, compare representations, and shift between stimuli according to a goal. In this phase, children can hold in working memory one or two instructions, understand the intentions of others, and reason pragmatically. These are the sources yielding material to be cognized, inferentially integrated, and generate the pool of knowledge children can call upon to sustain their interactions with the world. Thus, up to this age, cognizance mirrors the episodic or realistic representations of this period of life. However, the realistic representational mind still blurs boundaries between imagination and reality, enjoying the imaginary world as much as it may be deceived by it. It is thus no coincidence that, up to this phase, working memory is minimally predictive of more complex performance in language, cognizance, and reasoning. These higher-level competencies draw upon ensembles of actual or mental action, which are more complex than any working memory test can help discern. Anyone who converses with a 3- to 4-year-old child knows that the blocks of representations or interactions that the child can handle are vastly more complex than a score of 1–2 units of working memory.

Later on, at 6–8 years, as they are mastered, attention control and inhibition recede, and mental flexibility, working memory, and explicit awareness of inferential processes take their place as the major predictors of reasoning. By this phase, cognizance starts to reflect underlying inferential processes which are systematically called upon to organize experiences, memories, and knowledge about the world. It is natural that flexibility evolves into the conceptual fluency program of this phase and that working memory becomes a strong predictor of performance. The units handled are rules connecting representations singled-out from episodes or representational ensembles. Thus, working memory emerges as a measure of the representations that may be activated to substantiate or showcase rules or inferences based on them. The rule-based mind allows a well-organized representation of the world, which lacks cohesion and logical validation.

By the beginning of adolescence, attention control and flexibility are so well established that they are minimally, if at all, predictive of changes in awareness or inference. However, cognizance becomes increasingly accurate in cognizing similarities and differences between rules contributing to the abstraction of general principles bridging rules. Also, it becomes increasingly cohesive in its various dimensions and predictive of inference and problem solving. Notably, in this phase, performance in language, especially semantics, interfaces closely with cognizance. Thus, the principle-based mind adopts a suppositional stance allowing for a multi-perspective view of the world, where perspectives may be evaluated for truth and validity. Interestingly, recent research shows that in this phase awareness surfaces in perceptual processes at stages of processing previously thought to be automatic [Faivre, Mudrik, Schwartz, & Koch, 2014], blurring the boundaries between a preconscious automatic level in processing and a representational level of executively directed functioning.

Are then these four cycles “stages” in the classical sense? In a sense, they are. According to Lourenço [2016], to be considered a sequence of developmental stages, the sequence must be invariant, hierarchical, integrated, structured, and equilibrated. Strictly speaking, the sequence of cycles described here meets all five requirements. However, the cycles go beyond Piagetian or post-Piagetian stages. Notably, Feldman [2004] viewed Piaget’s stage theory as “the unfinished symphony of cognitive development.” He suggested that this symphony would be complete if the following conditions are met: “By shifting stage transitions to the midpoint of each stage, by adopting recursive transition processes from neo-Piagetian theories, by embracing décalage as systematic and necessary, and by using Piaget’s idea of the taking of consciousness, some of the main problems of his stages can be resolved in a satisfying way” [Feldman, 2004, p. 175].

We hope to have shown that the theory proposed here meets all four conditions. The cycles have the following properties: (a) they are recursive, (b) cognizance is upgraded with development into an increasingly powerful transition force driving change within and across cycles, (c) associated with major changes in developing the child’s insight about his or her own mind in the middle of each cycle, (d) a systematic explication of the interaction of domain-specificity with the operation of g is offered. However, if viewed from the point of their interrelations and overlap, these cycles are not stages in the classical sense because age boundaries in the change of each of the various processes involved project into each other’s time window. For instance, changes in attention control and related speed measures mark the beginning of cycles especially at 2–4 and 6–8 years. Changes in working memory mark the end of cycles at 4–6, 8–10, and 13–15 years. Changes in shifting and explicit cognizance about representations occur in the middle of cycles, at 5, 8, and 14 years. Changes in reasoning show up after these middle transition points reflecting the progression attained in the alignment and integration of representations in a given phase. This overlap of changes gives credit to Siegler’s [2016] wave model as an illustration of the intertwining of mental processes in development and learning.

Any theory of intellectual development has to account for increasing mastery of complexity without ascribing cognitive transitions to changes in working memory as such. The notion of Halford et al. [2014] of relational complexity may be a tool for specifying constraints on the concepts that can be grasped in each cycle. Specifically, the relational complexity of a task corresponds to the number of dimensions which must be simultaneously represented if their relations are to be understood. We stress, however, that we take relational complexity as a tool for analysing the representational dimensionality of concepts rather than the representational capacity of the individual. The findings summarized in Figure 2 strongly suggested that changes in reasoning are not driven by changes in working memory. Differences in representational resolution at successive cycles are associated with a different level of complexity in the concepts that may be grasped because they point to different underlying dimensions. This in turn is reflected in differences in the executive and awareness profile of each phase. Therefore, the direction of causality may go either way: changes in the resolution and executive mastering of representations cause improvements in the handling of relational complexity, and, when attained, a new level in mastering relational complexity enhances the range of concepts that may be grasped.

Specifying how learning occurs is important for any theory of intelligence or cognitive development. The present model suggests that both the nature and the possibilities of learning would vary with development. Specifically, early in development, a probabilistic inference mechanism sampling over statistical regularities in the environment may dominate [Tenenbaum, Kemp, Griffiths, & Goodman, 2011]. This type of learning in the episodic and the representational cycle seems necessary to generate a minimum representational and experiential base that would provide the representations and processes that would then be aligned, abstracted, and subsequently metarepresented into higher-order representations, rules, and principles. Later, similarities may be systematically searched for and conceptually aligned by reasoning, based on increasingly refined predictive rule-based and principle-based models. For instance, construction of mental models for the sake of evaluating the validity of conclusions in reasoning [Johnson-Laird & Khemlani, 2014] in later developmental cycles, especially the last, is guided by explicit representations of what is logically acceptable. Recent research suggests that model construction in deductive reasoning is not Bayesian [Markovits, Brisson, & de Chantal, 2015]. Therefore, reasoning becomes an integral component of learning, dominating over Bayesian learning.

Problems Solved by the Integrated Model

This model solves several thorny problems in developmental and psychometric theory. Here, we focus on three of them. First, why are later levels of intellectual development or higher scores of intelligence more difficult to attain than earlier levels? Second, do abilities differentiate from g with growth or increasing g? Third, how can we reconcile the existence of a strong g with powerful domains of mental functioning?

Developmental Deceleration, Scarcity of Higher Intelligence, and the Flynn Effect. Decreasing likelihood of attaining later developmental levels is related to the very nature of the main factor of developmental transition in cognitive development. Specifically, reflection and metarepresentation become increasingly difficult to perform because each next cycle's representations are more difficult to visualize by the mind's eye (e.g., compare episodic representations with principles), and they are semantically richer. Therefore, integrating representations into higher levels of executive control and reasoning becomes increasingly difficult because options increase exponentially, rendering fluid functioning less likely and mistakes more likely. It is stressed that attainment of the cycle of principle-based thought is rare in the general population, limited to the upper 5% of the population at 11–12 years and the upper 25% at the age 16–17 years (Fig. 6).

The scarcity of higher intelligence scores is associated with developmental deceleration. That is, higher scores of intelligence require solving problems associated with

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later developmental phases. Therefore, high scores are constrained by developmental constraints. Recently, we demonstrated that different phases of the cycles described here correspond to different IQ scores. We showed, for instance, that an IQ of 100 points, which is the intelligence of the two thirds of the general population in western counties, corresponds to integrated ruled-based concepts attained at the age of 9–10 years. Intelligence higher than 120 IQ points would require entering the cycle of principle-based thought [Demetriou & Spanoudis, 2017].

This very reason might also explain the secular increases in intelligence, which are known as the Flynn effect [Flynn, 2012]. Flynn found that there is an increase of about 10 IQ points every 30 years in the population of industrialized nations throughout the 20th century. Flynn ascribed the phenomenon to the expansion of education and the increasing symbolic demands of the technologically advanced cultures. These changes drive individuals to use and refine relational thought related to fluid intelligence. According to the present theory, the Flynn effect would be associated with both direct training of relational thought, but also reflection and cognizance that would be required to metarepresent and organize knowledge and problem solving that was associated with social and educational changes in the 20th century. The theory would also predict an inversion of the changes, with decreases in secular IQ in the industrial nations, if symbolic and abstraction demands placed by society would decrease. Flynn and Shayer [in press] did find this negative trend in Northern European countries.

Developmental Differentiation. Differentiation of mental abilities is interpreted differently in psychometric and developmental theory. Psychometric theory postulates that increasing g allows increasing differentiation of cognitive abilities [Jensen, 1998; Spearman, 1927]. Cognitive developmental theories postulated that increasing ability comes from increasing integration of mental structures at higher levels of abstraction [Case, 1985; Piaget, 1970]. The present model and findings offer a reason for this state of affairs. Both differentiation and intertwining of specific mental processes vis-à-vis g may happen but they are phase-specific and ability-specific. On the one hand, processes that are directly connected with the cognitive priorities of a phase appear to get increasingly connected to g. On the other hand, processes that are not central to these priorities may differentiate to reflect the fact that cognitive successes of more able individuals may be more variable than the successes of less able individuals. Naturally, highly able children have more cognitive capital to invest in their interests or match with environmental opportunities resulting with high performance in one domain and a lower one in another domain. Less able children tend to perform more uniformly across domains.

However, differentiation and integration occur in different aspects of mental development. Differentiation applies primarily to mental functions themselves. The resolution of cognizance increases across cycles, increasingly differentiating between mental functions, such as attention, WMC, and inference, allowing a more refined regulation of mental processing. Integration applies primarily to representations. Cycle transitions reflect increasing integration of representations, yielding hubs and pointers to navigate between representations and processes enhancing their scope and accuracy vis-à-vis the environment. Cognizance (and ensuing metarepresentation) is an integrative and a differentiation tool because it drives the search for relations underlying concepts or processes, accentuating differences when relations are not found.

Minimizing the Fade-Out Effect. The present model contributes to the integration of developmental and psychometric theory because it shows how powerful developmental processes may contribute to the nature and timing of individual differences in learning. Our studies, summarized in our fourth state-of-the-art conclusion, suggested that learning gains are developmentally specific and, often, domain-specific. Affecting an earlier cycle would not necessarily transfer to the next cycle or to another domain, even if it raises its level of readiness. Also, a cycle-specific learning program may change a process at the level targeted, but gains do not fully consolidate unless they are embedded in the supportive frame of operating at a higher level developmental cycle. Therefore, transfer to processes specific to the next cycle would not be attained unless learning comes repetitively in accordance with the needs of each cycle, until gains are locked into the system as habitual ways of dealing with problems. Therefore, learning programs must recycle with intellectual development cycles each time boosting the processes that relate to the emergence and consolidation of each cycle, i.e., facilitate mapping actions onto objects and their representations, build awareness of representations and their constraints, refine understanding of process- and rule-specific constraints of knowledge and inference, and evaluate conceptual spaces for truth and validity in the four cycles, respectively.

The theory presented here bears implications both for brain organization and development, artificial intelligence, and education. For instance, the various structures and processes described here must be identifiable in the brain [see Demetriou & Spanoudis, 2018; Haier, 2017]. Drawing upon these structures must facilitate the development of artificial intelligence agents simulating the human developing mind [Cangelosi & Schlesinger, 2015]. Implementing the learning principles proposed here must improve learning in education [Demetriou & Spanoudis, 2018]. Failure to realize these implications would require accommodating the theory.

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