Chapter 3
Mind and Intelligence: Integrating Developmental, Psychometric, and Cognitive Theories of Human Mind

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Abstract This chapter summarizes a comprehensive theory of intellectual organization and growth. The theory specifies a common core of processes (abstraction, representational alignment, and cognizance, i.e., AACog) underlying inference and meaning making. AACog develops over four reconceptualization cycles (episodic representations, realistic representations, rule-based inference and principle-based inference starting at birth, 2, 6, and 11 years, respectively) with two phases in each (production of new mental units and alignment). This sequence relates to changes in processing efficiency and working memory (WM) in overlapping cycles such that relations with efficiency are high in the production phases and relations with WM are high in the alignment phases over all cycles. Reconceptualization is self-propelled because AACog continuously generates new mental content expressed in representations of increasing inclusiveness and resolution. Each cycle culminates into an insight about the cycle's representations and underlying inferential processes that is expressed into executive programs of increasing flexibility. Learning addressed to this insight accelerates the course of reconceptualization. Individual differences in intellectual growth are related to both the state of this core and its interaction with different cognitively primary domains (e.g. categorical, quantitative, spatial cognition, etc.). We will also demonstrate that different levels of intelligence expressed through IQ measures actually correspond to different types of representational and problem-solving possibilities as expressed through the AACog reconceptualization cycles.

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3.1 Introduction

The human mind was 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 intersections. Differential research uncovered stable dimensions of individual 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; Hunt 2011; Jensen 1998), but underestimated their development. Developmental research mapped changes in intellectual possibilities through life span (Case 1985; Flavell et al. 2001; Overton 2012; Piaget 1970) but underestimated individual differences in development. Cognitive psychology mapped cognitive mechanisms, such as working memory (Baddeley 2012) and reasoning (Johnson-Laird 2001), but ignored intra- and inter-individual variation and development. Neuroscience highlights the neuronal bases of cognitive functions and development (Shaw et al. 2006) but we do not yet understand how the brain generates cognition. Understanding the mind as a whole requires a theory that would accommodate (i) its architecture and development, (ii) individual differences between both, and (iii) learning at different phases of development.

This article summarizes one such theory. Here we focus on five aspects of the theory. First, we elaborate on the composition of the central core of intellect. Our aim is to show what processes are involved in understanding and problem solving. Second, we show how this core develops through the years. That is, we will discuss what kinds of executive and inferential possibilities are associated with successive phases of development from birth to adulthood. Third, we will elaborate on the relations between changes in executive and inferential possibilities and two important factors of cognitive efficiency: processing efficiency and working memory (WM). Fourth, we discuss research highlighting how cognitive development may be boosted by systematically organized learning environments. Fifth, we focus on individual differences in intellectual attainment and development.

3.2 Embedding the Mental Core into Mental Architecture

The human mind comprises specialized systems carrying out different tasks for understanding or problem solving. They are as follows:

(i) Several domain-specific thought systems ground the mind in reality (e.g., quantitative, spatial, causal, and social thought).
(ii) A central workspace allowing representation and processing of current information. Working memory is the classic conception for the nature and role of central workspace (Baddeley 2012).

(iii) Consciousness allowing self-monitoring, self-regulation, and self-evaluation.
(iv) Inferential systems allowing integration of information (e.g. inductive, analogical, and deductive reasoning).

Figure 3.1 illustrates this general architecture.

The interface between all systems is a central triple-process mechanism: abstraction, alignment, and cognizance, the AACog mechanism. Abstraction extracts similarities between representations according to shared statistical regularities or other types of commonalities. Alignment inter-links and relates representations in search of their similarities. Cognizance is the component of consciousness focusing on the mind itself. So defined, cognizance generates reflection and mental models of relations allowing feedback loops where cycles of abstraction, alignment, and inference may become the object of further abstraction and alignment.

AACog lies at the center of interaction between systems underlying various processes studied by research (see Fig. 3.1). Specifically, representation and organization of domain-specific information in working memory allows episodic integration that preserves the particular spatial and time structure of events as required. Imposing an explicitly represented goal on the functioning of working memory underlies executive control of mental and behavioral action. The interaction between consciousness and inference allows metarepresentation which encodes similarities between representations into new representations. Finally, processing, integration and evaluation of domain information and concepts underlies

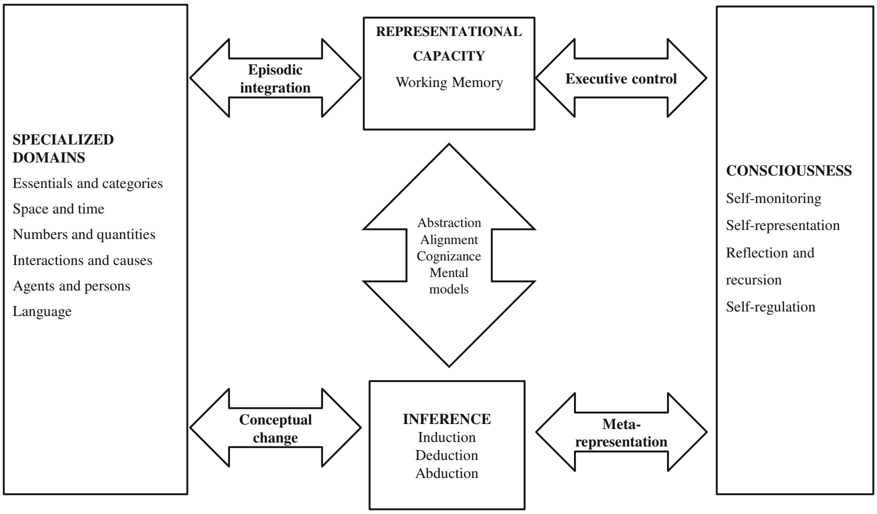

Fig. 3.1 The general architecture of the human mind

conceptual change than enhances one's knowledge base and problem-solving possibilities (Demetriou and Kazi 2006; Demetriou et al. 2008, 2014a, b).

AACog is partly similar to general intelligence as specified by Spearman (1927) or fluid intelligence, as specified by Cattell (1963). In Spearman's (1904) classic theory, general intelligence (or g) is defined as the eduction of relations and correlates. This is relational thought abstracting (i) relations between objects or events based on their similarities and (ii) relations between relations based on the reduction of similarities into rules and higher order principles relating these rules (Carroll 1993; Jensen 1998). In current psychometric theory these processes are associated with fluid intelligence (Gf), which is differentiated from Cf, Gc (i.e. knowledge and skills emerging from the functioning of Gf) (Cattell 1963; Gustafsson and Undheim 1996). In classical developmental theory, this core comprises reversible mental operations allowing understanding of stability and change in the world and grasping the (physical or logical) implications of alternative physical or mental actions (Piaget 1970). This core first organizes mental activity at successive developmental levels. However, cognizance is not even recognized as a factor in psychometric theory (Jensen 1998). Developmental theory did recognize it but considered it a result rather than an effective factor of change (Piaget 2001).

In a similar fashion, cognitive science assumes that there is a language of thought (LOT). According to Fodor (1975), LOT comprises rules underlying the combination of mental elements, such as words or mental images, that preserve stability and truth over the transformation of mental elements: if they are true, their transformation also yields true results. For example, "cat", "dog" and "animal" are all valid symbols standing for some reality. Thus, their combination results in true inferences. For instance, both cats and dogs are animals; thus, they both move around to find food; there are more animals than dogs or cats, etc. That is, once the input is true, the output (conclusions, interpretations, etc.) is also true.

For many, the rules of LOT are the rules of logical reasoning, be they the rules of logic (Rips 1994) or mental models (Johnson-Laird and Khemlani 2014). Carruthers (2002, 2008, 2013) postulated that language is instrumental in the formation of the rules of LOT, especially syntax. He suggested that syntax in language is a major integration mechanism: recursiveness, hierarchical organization, compositionality, and generativity, the fundamental properties of syntax, render language a major influence on reasoning and concept formation. He also maintained that language is related to awareness because language is the vehicle for externally representing mental objects including propositions. Thus, language renders thought available to monitoring and awareness (Carruthers 2008). In a similar fashion, other scholars suggested that language makes executive control possible because it allows individuals to address self-regulatory instructions to themselves (Perner 1998).

In a recent study, we investigated the relation between the psychometric equivalent of AACog, several aspects of executive control and cognizance, and each of several domain-specific processes of language and various domains of reasoning. Specifically, this study involved 9–15 year-old participants who were examined via a large battery of tasks addressed to attention control, flexibility in shifting, working memory, inductive, deductive, mathematical, causal and spatial reasoning, and three aspects of language, namely syntax, semantics and vocabulary. Speaking in terms of structural equation modelling, we created a first-order factor for each of these domains. To capture AACog and specify its relations with language and the various executive control processes we adopted a rather unconventional approach to modeling. Specifically, we created a second-order factor that was related *to all domain-specific language and reasoning factors but one*. This second-order 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. Obviously, a high relation between the reference factor and the common factor would indicate that the common factor carries much of the constituent properties of the reference factor. In turn, the reference factor was regressed on attention control, cognitive flexibility and working memory. For instance, if syntax, as maintained by Carruthers (2002), or inductive reasoning, as maintained by psychometric theory (Spearman 1927), are privileged proxies for the core of intelligence, the relation between these reference factors and the second-order factor would be higher than its relation with any other domain-specific factor. Also, the relations between these reference factors and the executive control factors would be similar to the direct relations between the second-order factors and these executive control factors. The results of these models are summarized in Fig. 3.2.

It can be seen in Fig. 3.2 that the relation between the reference factor and the common factor was always very high (0.8–1.0) regardless of which of the domain-specific factors was lifted to the status of reference factor. These results align with Gustafsson's (1984) finding that gf and g are practically identical. In the same

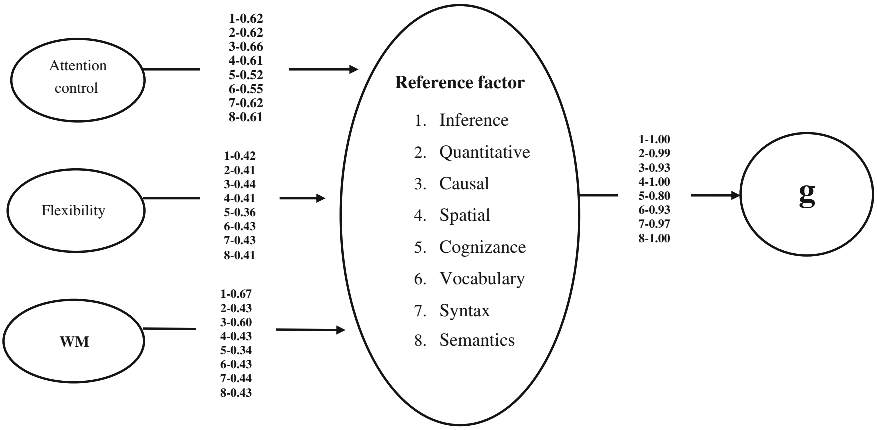

Fig. 3.2 Structural relations between g, reference factors, and attention control, cognitive flexibility, and WM. *Note* The figure summarizes eight models in which first-order factors standing for each of the domains are specified. All but one (the reference factor) was regressed on g, g was regressed on the reference factor, and the reference factor was regressed on all four factors standing for aspects of executive control. The values in the figure come from each run of the model. The fit of all models was always good (all comparative fit index (CFIs) > 0.9)

direction, other research showed that Cf and g relate very highly (Kyllonen and Kell, this volume). Obviously, these results do not support the assumption that syntax or reasoning (in any domain) has a privileged relation with g. Rather, these results suggest that all domains contain the common core to a large extent so that any one of them can reliably stand for it. This interpretation is strongly supported by the fact that all reference factors were significantly, and about evenly, related to all three executive control factors (varying between 0.4 and 0.6), just as in the model where the general factor was directly associated with these executive control factors.

A series of studies focused on the relations between g and cognizance. These studies involved participants from 4 years of age to adulthood, examined by age-appropriate tasks. For example, reasoning in preschool children was examined by various classification, simple arithmetic, and pragmatic reasoning tasks. Cognizance was examined by tasks addressed to awareness of the origin of their mental processing, such as perceptual and environment-based or inferential. We found that cognizance was always an important factor of intellectual functioning and development, if examined by age-appropriate tasks. Specifically, cognizance appears as awareness of the perceptual origins of knowledge at 4–6 years; at 6–8 years the inferential aspects of knowledge took over as a mediator between all reasoning processes and Gf (Spanoudis et al. 2015). Later, in adolescence it was awareness of the logical aspects of reasoning (Christoforides et al. in press). Thus, on the one hand, "self-evaluation and self-awareness concerning the relevant mental operations are very low and inaccurate at the beginning, and they tend to increase and to become more accurate with development until the end of the cycle." (Demetriou et al. 2010, pp. 329). On the other hand, language and cognizance get gradually intertwined with age (Makris et al. in press). However language does not have any privileged role in expressing g. Thus, language may become a tool for the efficient handling of representations in the service of cognizance. However, other types of representation may do this job equally well.

These findings suggest that the common core cannot be equated with psychometric g, Gf, or the mental structures dominating in developmental theories. These classical structures are too dependent on inferential processes, while the core identified here also relates to processes which are minimally inferential, such as vocabulary. As noted in the introduction, AACog is minimally inferential in that it involves abstraction and alignment processes allowing the search for and encoding of similarities or regularities in the environment into representations and concepts. Combinativity and generativity of some sort (including Piagetian reversibility) may be part of this encoding process. However, in itself, AACog is silent about the exact identity of processes as these may vary across domains or developmental levels. In conclusion, one might argue that the seeds for inference, cognizance, and language that contributed to the formation of the core identified here co-evolved for a very long period of time, probably starting since the Neanderthals first appeared, about 500,000 years ago (Dediu and Levinson 2013). Thus, they are so inextricably linked, genetically, brain-wise, ontogenetically, and culturally, that their interactions always go both ways. In combination, these processes allow for the compositionality, recurrence, generativity, and hierarchical integration of mental action sequences engaged by problems requiring understanding and solution. Through the millennia, evolution abstracted this structure from various domains, including language, and projected it to a level higher than any one of them. For instance, these processes might underlie both the interlinking of propositions in deductive reasoning in search of a true inference and the arrangements of words and sentences to convey meaningful messages in language.

3.3 Mapping the Development of the Executive Core and Its Transcription into Reasoning

The AACog mechanism (i.e. abstraction, alignment, and cognizance) is active in its entirety since the beginning of life. However, the operation of each of the three functions and their relative contribution may vary with development and/or experience (Demetriou and Kyriakides 2006; Demetriou et al. 2011, 2014a, b). Specifically, early in development abstraction may induce similarities between objects or patterns of information based on a simple probabilistic inference mechanism sampling over statistical regularities in the environment (Tenenbaum et al. 2011). Later on, in toddlerhood, abstraction may be based on inductive inference, which may grasp relations between representations and bridge conceptual spaces. Later, in primary school, deductive inference is possible, which allows checks for consistency, validity, and truth. Thus, there seems to be an executive core in AACog which comprises the representational capacity to hold a mental or behavioral goal active, the general search and combinativity operations allowing the alignment of this goal with a minimum of one environmental representation and action, and the abstraction–metarepresentation processes that may encode a decision. This may be described as an executive control program that evolves through four major developmental cycles, with two phases in each. New representations emerge early in each cycle and their alignment dominates later. Below we will specify the program for each cycle and highlight how it is transcribed in reasoning. It is noted that the executive programs are transcribed in each of the domains shown in Fig. 3.1, in a fashion similar to reasoning. The interested reader is referred to other sources for an exposition of development in the various domains (e.g. Demetriou et al. 2014a, b).

3.3.1 Executive Control and Reasoning

Episodic executive control. At the age of 15 months, infants recognize themselves in the mirror, indicating awareness of their facial identity (Gallup 1982; Povinelli 2001). By 18 months, infants seem to have an awareness of knowledge as a source of goals and actions; for instance, they infer that someone who saw where a reward was hidden will look for it at that place (Sodian et al. 2012). In fact, infants show signs of explicit reflection on their past experience by the age of 20 months: ND, the first author's grandson, obviously reflecting while traveling in the car, said: "Otherwise …". What do you mean Nicolas? "Otherwise you will fall down Nicolas". Clearly referring to a conversation with his grandmother who warned him in the morning: be careful, because otherwise you will fall down and harm yourself! (conversations with ND, my grandson, at the age of 20 months). This evidence supports the assumption that infants start to be able to perform executive control by the end of their second year. However, episodic executive control is constrained by the very nature of episodic representations: it is dependent on the availability of stimuli that would sustain an episodic representational sequence (e.g. an interesting object or sound where the infant could turn). Therefore, the scope of control is constrained by the variation of stimuli: by the time a new attractive stimulus appears a new executive concern may initiate which activates a new sequence of actions. However, it is representationally mediated in that the triggering stimulus is represented together with an expected action sequence (pen → write → paper). Thus, in this cycle, the executive program may be described as a "perceive–represent-action" program: It is stimulus-activated (e.g. "this is a pen") but it is mediated by a representation of a past action (e.g. I wrote using it) which is transformed into a present action (writing). Imitation in this cycle may also be analyzed as a focus–represent-program in that an attractive behavioral episode by a model is translated into the infant's own actions (Carey 2009).

Episodic reasoning. Reasoning in this cycle is exclusively inductive, generalizing over episodic representations based on perceptual similarities (Carey 2009), and regularities in the episodic structure of events. Thus, in this cycle, inference emerges as an abstraction of the episodic blocks. When encoded they may resemble schemes of reasoning, such as conjunction or implication. For instance, Nicolas stated, obviously aligning the representations of grandfather and grandmother into a conjunctive complex: "grandma, grandpa; grandma AND grandpa" (conversations with ND, my grandson, at the age of 19 months old). This is evident in language learning. For instance, associating an object with a novel name (i.e. "this is a dax" or "this is a diffle") leads children to infer that other objects of the same shape are "dax" or "diffle" (Becker and Ward 1991; Landau et al. 1988). These inferential sequences may be mapped onto the three components of the "focus–represent–respond" episodic executive program. That is, (i) looking for a relation, (ii) encoding it into a specific representation (e.g. togetherness of grandma and grandpa), and (iii) spelling it out (e.g. AND) would correspond to (i) focus, (ii) represent, and (iii) respond, respectively.

Representational executive control. Early in this cycle, from 1½ to 2 years, episodic representations are projected into representations encompassing properties going beyond their episodic origin. For instance, the "mum and dad" representation is projected from the mother and father pair related to the infant to stand for other "women–men" pairs. As a result, infants start to intentionally scan representations, search for specific elements in them, and align them. Thus, by the age of 3–4 years, executive control is expressed as a *representational control executive program* allowing toddlers to focus on 2–3 interrelated representations and alternate between them while both are in focus. Technically, this program is represented by various inhibition tasks, such as the go/no go and Stroop-like tasks. These tasks require the child to inhibit responding to one perceptually strong stimulus in order to respond to a goal-relevant stimulus that is somehow masked by the strong stimulus. When established at about the age of 4–5 years, it fully accounts for working memory, rule-based sorting, dual representation, theory-of-mind, appearance-reality distinction, and dimensional sorting. All of these seemingly different abilities appear reducible to a simple “focus–scan–choose–respond” program enabling children to stay systematically focused on a goal (Demetriou et al. 2014a, b). This enhances the time perspective of the toddler because earlier experiences underlying representational blocks get into the organization of present action.

Pragmatic reasoning. Inductive reasoning is well functioning in this phase. Preschool children can easily solve Raven-like matrices varying along a single dimension, such as color or size. Deductive reasoning at this phase reflects the sequence of events in an episodic sequence rather than an inference: “It rains, so we need our umbrella.” At the second phase of this cycle two-dimensional, Raven-like matrices (animal and color, color and size) may be solved, indicating an ability to search and analyze representations and align their components. Aspects of deductive inference appear at the age of 4–5 years in the form of pragmatic inferences related to deals. For instance: “We agreed that if I eat my food I can play outside; I ate my food; I 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 the “focus–scan–choose–respond” representational executive control program of this cycle allows them to envisage alternative choices.

Rule-based executive control. In the cycle of rule-based concepts the time perspective widens extensively because rules connecting representations bridge the past with the present and future. This gives alternative plans to consider. Thus, in primary school, executive control is upgraded into *a conceptual fluency program* allowing children to shift between conceptual spaces (e.g. various object categories), activate space-specific instances, and interrelate them according to specific conceptual or procedural constraints. This is an “explore–compare–select–shift–reduce” program allowing children to shift between conceptual spaces and inter-link them according to one or more rules. For example, children at 8–9 years of age can perform well on tasks requiring a shift between conceptual spaces by recalling words starting with particular letters (e.g. Brydges et al. 2014), second-order rules in the Dimensional Change Card Sorting (DCCS) task, and second-order theory of mind tasks. We showed that this kind of mental fluency dominates as a predictor of reasoning and problem solving at the end of primary school (Spanoudis et al. 2015; Makris et al. in press). Thus, it seems that mental fluency is added to representational-action inhibition processes.

Rule-based reasoning. Early in this phase, analogical reasoning becomes flexible enough to handle several clearly present dimensions in 3 × 3 Raven-like matrices, suggesting that inference is fluid enough to access individual representations, align them, and bind them together according to underlying relations. This is clearly reflected in deductive reasoning, which emerges explicitly at this phase. It becomes obvious in the integration of modus ponens and modus tolens into a fluent inferential ensemble (i.e. if p then q; $q \rightarrow p$; not $q \rightarrow$ not p). This understanding suggests that the rules underlying relations between objects or events are explicitly metarepresented into a system specifying how different inferential spaces are interrelated. In turn, this metarepresentation transforms inductive imperatives into deductive necessities. The rules are as follows:

(i) Different representational spaces may have different inferential constraints (e.g. birds fly, mammals walk, fish swim, etc.) yielding different inductive implications about individual elements in each space (e.g. blackbirds fly, elephants walk, sharks swim, etc., respectively).
(ii) Moving across representational spaces is possible; however, shifting across spaces (e.g. imagining that "elephants are birds") implies accepting the constraints of the new space (i.e. "elephants must fly").
(iii) The primary premise defines the constraints of the space; the secondary premise only specifies an application domain of this space.

Therefore, actual properties (e.g. elephants are mammals) are overwritten once they conform to the deductive rule "A & B, $A \rightarrow B$", which cuts across spaces. Obviously, moving across conceptual spaces and integrating into logical rules is possible because the "scan–compare–reduce–select–shift" conceptual fluency program of this cycle allows these possibilities.

Principle-based executive control. Executive control in adolescence integrates the flexibility and planning already established in the previous cycle. Technically speaking, however, changes in executive control in this cycle are not related to changes in selective attention or cognitive flexibility as such because these processes reach a ceiling level by about 13 years. In this cycle, executive control is extended into a suppositional–generative program ("suppose–derive–evaluate") enabling adolescents to co-activate conceptual spaces and evaluate them vis-à-vis each other and truth–validity–value systems that are deemed relevant. Thus, this is *an inferential relevance mastery program* opening the way for fully capturing reasoning and epistemic systems.

Principle-based reasoning. Adolescents in this phase may solve complex Raven matrices requiring grasping a principle underlying several seemingly different transformations. Obviously, these problems require representational alignment that is mastered in the previous phase. In addition, however, they also require explicit encoding of the relations generated by alignment into a representational token of these relations as such. This may be an explicit grasp of the transformation connecting the matrices or the mathematical relation running through a series of mathematical ensembles. Eventually, they may deal with multiple hidden relations or build analogical relations within and across levels of different hierarchies (e.g. students–teachers–education may be related to children–parents–family).

In deductive reasoning, children start to grasp fallacies when expressed in familiar content. Eventually, at the second phase they may process the formal representation of fallacies as in the famous Wason's (1968) task. Grasping the fallacies entails only one further metarepresentational step in concern to the reasoning possibilities mastered at the end of the rule-based cycle. This is the suppositional stance that brings disparate representational spaces back into the deductive rule as a deductive moderator "$A_{(\text{but probably also } C,\, D,\, E,\, \ldots)}$ & B". When A vis-à-vis B is represented as one option among others the modus ponens affirming the consequent and the modus tolens denying the antecedent equivalence necessarily breaks because asserting B (affirming the consequent) or denying A (denying the antecedent) hints to the options beyond A. Obviously, grasping and integrating these rules into a smoothly running metalogical system is a major developmental construction that takes place throughout the last two cycles of development. Thus, the "suppose–derive–evaluate" inferential relevance mastery program of this cycle expresses itself via the deductive moderator that can place truth weights of the various alternative choices that can be deduced from a logical argument (Christoforides et al. in press).

3.4 Changing Patterns in the Speed-Working, Memory-Intelligence Relations

Research in all traditions has sought to decompose the mental core into more fundamental components. Various aspects of attention control (the ability to select and process a stimulus property that is currently relevant, inhibiting more attractive but irrelevant stimuli, shifting between stimuli following relevant directions), executive control (laying down and implementing a plan aiming at a goal by going from step to step), and working memory (storing, accessing, and recalling information according to a goal) were considered as the building blocks of the mental core. A hierarchical cascade was proposed as the model of the relations between these processes. This model postulated that each process is embedded into the next more complex process residing higher in the hierarchy (Fry and Hale 1996; Kail 2007; Kail et al. 2015). Attention control → flexibility in shifting → working memory → reasoning and problem solving.

The cascade model may be promising from the point of view of reductive science because it aims to reduce complex processes to simpler ones. However, it is limited by its assumption that the cascade relation between processes remains stable in development. In a series of studies we explored the development and interrelations between these processes from early childhood to adulthood. Our aim was to pinpoint possible changes in these relations with development. Individuals solved tasks addressed to a succession of reasoning levels according to the cycles described above. These tasks addressed reasoning and problem solving in various domains, such as class, quantitative, spatial, causal, and propositional reasoning. Children also responded to speeded performance tasks addressed to attention control and executive control at various levels of complexity, and they solved working memory tasks addressed to various modes, including verbal, numerical, and visual/spatial information (e.g. Demetriou and Kyriakides 2006; Demetriou et al. 2013). Some of these studies are summarized in Fig. 3.3. Technically speaking, the reasoning curve in Fig. 3.3 stands for a score specifying the developmental phase of individuals. In psychometric terms, this score would be regarded as an index of Gf. The other two curves in Fig. 3.3 stand for performance on processing speed tasks (expressed in seconds) and verbal working memory tasks (varying from 1 to 7 units).

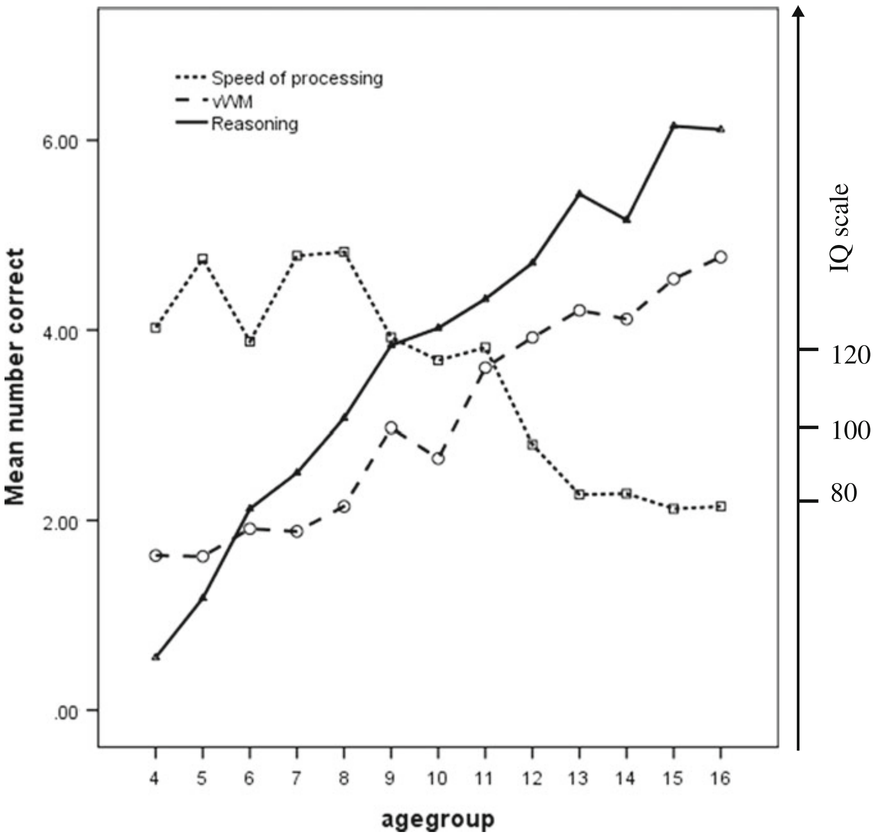

Fig. 3.3 Development of speed of processing, verbal WM (1–7), and reasoning (AACog) (logits +3, 0–1) as a function of age. *Note* Numbers on the left stand for working memory capacity. Numbers on the right stand for IQ points as obtained after the transformation of the reasoning (AACog) logit score into an IQ-like score as explained in the text. Speed varied from 0.73 (at age 15) to 1.66 s (at age 8) and it was adapted in the figure

All processes improved systematically with age. These patterns give the impression of direct and linear causal relations between these processes. However, this is not the case. For instance, we found that reasoning attainment of individuals with high WM was always closer to that of similar aged peers with low working memory rather than to that of older individuals. Results for speed and control were very similar (Demetriou et al. 2013). These results suggest that these factors minimally accounted for age-related changes in reasoning. 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). In this model, reaction time (RT) was regressed on age, working memory was regressed on age and RT, and reasoning was regressed on age, RT, and working memory. This model can show how the relations between these constructs vary with developmental phase, if indeed they do at all. The overall pattern obtained is summarized in Fig. 3.4.

It can be seen that the strength of these relations varied periodically with age. Specifically, in the early phase of each cycle the RT–reasoning relations were high and the working memory–reasoning relations were low. This relation was inverted in the second phase of each cycle, when the RT–reasoning relations dropped and the working memory–reasoning relations rose drastically. Recently, these relations were also tested by modeling 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. It is emphasized that these cycles were fully replicated, indicating that this is a robust developmental phenomenon (Demetriou et al. 2013, 2014a, b).

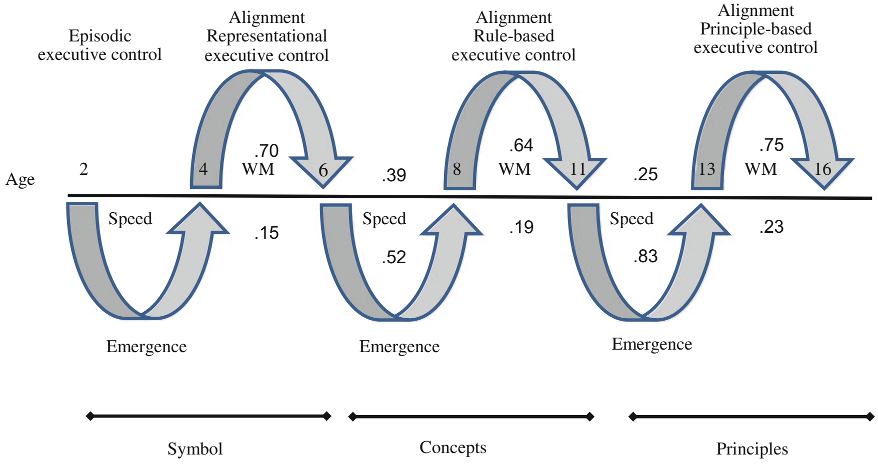

Fig. 3.4 Relations between speed, WM, and reasoning (AACog) according to developmental cycles and phase. *Note* Values show mean structural relations between speed and reasoning (*below the age line*) and working memory and reasoning (*above the age line*) in successive developmental phases

In fact, we recently showed that this recycling model involves executive control as well. That is, the various aspects of executive control are differentially related to AACog, according to developmental phase. Specifically, Demetriou et al. (submitted) showed that control of attentional focus culminates at the age of 5–6 years and then fades out as a predictor of AACog. At 6–8 years inhibition control regarding stimulus–response pairing automates, allowing children to efficiently focus on relevant information. A complementary study involving 9–15 year-old children showed that in the 8–10 year-old phase inhibition control and flexibility in shifting dominate as predictors of AACog. In the 11–13 year-old phase, these two aspects of executive control fade out as predictors of AACog and working memory and cognizance emerge. Eventually, in the 13–15 year-old phase both working memory and cognizance dominate emerge as the best predictors of AACog (Makris et al. in press). These results indicate that, with age, control is passed over from processes interfacing representation with the environment (e.g. stimulus recognition, reading, etc.) to processes primarily applied on the relations between representations and mental processes (e.g., working memory, inference, etc.).

At the beginning of cycles, processing speed on control tasks may increase for several reasons. For instance, individuals master the new executive program, increasingly automating their 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 rapidly 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, WM is a better index because alignment and inter-linking of representations both requires and facilitates WM. It is stressed that it is the executive and integrative processes in WM, rather than plain storage, that was found to predict reasoning changes in the second phase of each cycle. However, signifying developmental changes at the beginning of cycles (speed) or individual differences in their implementation at the end (WM) does not imply that these factors are the causes of change or individual differences. Where is then developmental causality if not in speed or WM? We will show in the following section that cognizance is the primary factor of transition across phases and cycles.

3.4.1 Learning to Think and Reason

We conducted several studies to examine if changing intelligence is possible and what is the crucial mechanism that must be targeted to attain change. One of these studies examined whether training inductive reasoning in mathematics would improve performance in several aspects of mathematics and if this would generalize to other aspects of intelligence. This study involved 11-year-old children. We showed that change in the domain of mathematical reasoning was considerable soon after the end of the intervention, although not all of it was sustainable over time. However, the gains did transfer to domain-free analogical reasoning tasks and, to a lesser extent, to other domains, such as deductive and spatial reasoning, differing from the processes trained. Interestingly, gains in deductive reasoning continued to improve from second to third testing, when they dropped in other domains. Also, there was a transfer to domain general processes, reflecting processing and representational efficiency, such as attention control and WM. At the same time, the impact of the program was not significant enough to modify thought processes that belong to a next cycle of development, namely the principle-based cycle.

Another study focused on the critical mechanism for transition. Specifically, this study let 8-year-old and 11-year-old children become aware of the logical characteristics of the four basic logical schemes of conditional reasoning explicated above (i.e. modus ponens, modus tolens, affirming the consequent, and denying the antecedent) and trained them to build and mentally process mental models appropriate for each, 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 tolens). The aim was to examine if enhancing cognizance about these schemes and processes would result into transition from rule-based to principle-based deductive reasoning. Moreover, we examined how this enhancement influenced transition on the various processing and intelligence processes discussed above, such as processing efficiency, WM, inductive reasoning, and cognitive flexibility. The main findings of this study are summarized in Fig. 3.5. We found that the transition did occur and it was fully mediated by awareness for both age groups. In terms of spontaneous developmental time, this short training program pulled children up by an almost full developmental phase, preserving a distance between ages. 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. Building cognizance was strongly related to attention control and this relation increased systematically with increased training. Thus, awareness training in the cycle of rule-based inference generated insight into the logical implications of the various schemes but this insight was not crystallized into the metalogical rules that would allow handling any problem regardless of familiarity. These rules, which require an explicit representation of the pairwise relations between the schemes, were mastered by the 11-year-old children, who acquired the *suppositional stance.*

This pattern of effects, both positive and negative, bears an important educational implication. Learning programs must cycle along the cycles of development themselves. That is, they must be tailored to successive developmental cycles through the end, each time boosting the processes that relate to the emergence and consolidation of each cycle. Affecting an earlier cycle would not necessarily

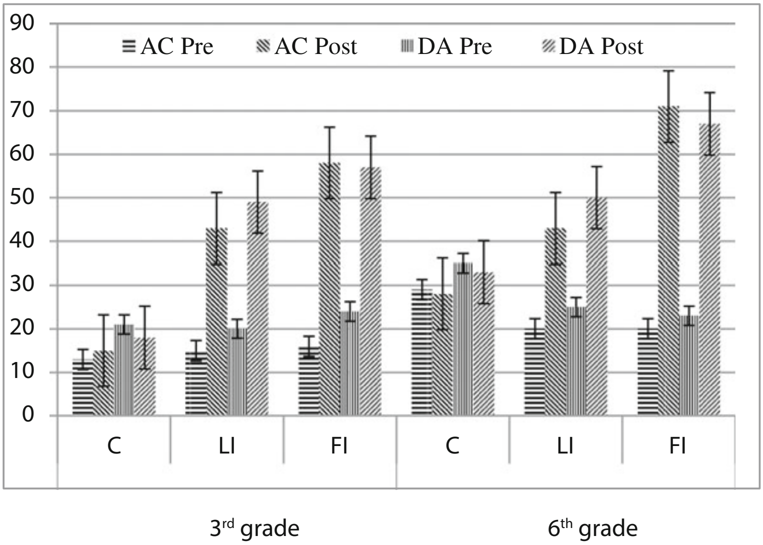

Fig. 3.5 Mean percent success on affirming the consequent (*AC*) and denying the antecedent (*DA*) reasoning tasks as a function of primary school grade and experimental condition (*C*, *LI*, and *FI* stand for control, limited instruction, and full instruction)

transfer to the next cycle, even if it raises its level of readiness. This may render observed gains developmentally specific to a large extent, suggesting that intelligence and related cognitive processes are constrained by powerful developmental cycles that set strong limits to learning. Thus, instruction-based change in various aspects of these processes may be temporary, as shown here. Sustainability and transfer of cognitive change to another cycle may also be constrained by brain-dependent developmental dynamics (Shaw et al. 2006).

This interpretation may explain the distressing fade out effect of learning studies aiming to increase intelligence, such as the Head Start Program. These studies are successful as long as they continue soon after they end. Gains of up to 8 points on the IQ scale were observed by the completion of programs. However, these gains fade out fast and 2–3 years after the end of intervention they are almost completely gone (Protzko 2015). Our studies summarized above suggested that learning gains are developmentally specific. That is, they may change a process at the level targeted, but they do not fully consolidate and automate unless they are embedded in the supportive frame of operating at a next higher level developmental cycle. Therefore, transfer to processes specific to the next cycle, such as scientific thinking, 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 (Papageorgiou et al. 2016).

3.5 Aligning Mental Age with Developmental Cycles

Individuals differ in rate of development and ultimate attainment because of hereditary and environmental reasons. Individual differences in IQ are considered to be generally stable, especially between 5 and 6 years of age to middle age. Correlations between IQ scores obtained at different ages in this span are generally high (between 0.5 and 0.7). However, intelligence within the individual may change, both at the individual and the collective level. At the individual level, it is well established that education increases intelligence by about 1–4 IQ points for each extra year of schooling (Ceci 1991; Gustafsson 2008). At the collective level, according to the so-called Flynn effect, general intelligence increases in the general population over the years. Flynn (1987) discovered that IQ increased by about 10 IQ points every thirty years since the beginning of the 20th century.

What is the developmental implication of these effects? Answering this question requires an integration of psychometrics with the developmental expression of intellectual attainment that would allow one to translate performance on IQ tests into developmental levels. This would enable one to transfer knowledge from developmental research to learning, in order to specify possible developmental constraints to learning aiming to increase intelligence. In sake of this aim, we transformed attainment on our battery of reasoning development into an IQ-like score. This attainment is indicated by the reasoning curve in Fig. 3.3. In a sense, this transformation aligns mental age with the levels associated with the developmental cycles discussed above. The reader is reminded that Binet defined intelligence as the quotient (hence IQ) of (MA/CA) × 100. Nowadays, IQ is defined as $(z \times 15) + 100$, where z is the z score of the individual on the test and 15 is the standard deviation of the population.

It is noted that this battery involved tasks addressed to all domains of reasoning specified above (i.e. categorical, causal, spatial, analogical, and deductive reasoning). These tasks were systematically scaled in difficulty to tap all three cycles of development spanning from the age of 3–4 to 17–18 years. We also note that the relation between this battery and performance on the WISC test is very high (circa 0.8) (Case et al. 2001). The total score on this battery was transformed into an IQ-like score in the fashion that the raw score on the WISC be transformed into an individual's IQ. That is, the raw score was transformed into a z score and this was then fed into the IQ equation: $\mathrm{IQ} = (z \times 15) + 100$. Therefore, this transformation shows how different levels of IQ correspond to the cycles of intellectual development outlined here. It can be seen in Fig. 3.3 that an IQ of 100 points, which is the intelligence of 2/3 of the population corresponds to the attainments of the 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. It is noted that this transformation was also applied on the performance attained by a Croatian sample of 8–17-year-old participants on Raven's standard progressive matrices (Zebec 2015). We obtained very similar results.

Mapping the effects of education noted above at both the individual and the collective level would suggest that, on average, the sheer effect of 12 years of primary and secondary education would correspond to an increase of about 12–18 degrees on the IQ scale, which is equal to about one standard deviation on the IQ scale. This is important but not dramatic. For most people it would imply improvements within, rather than across, developmental levels, mostly related to the consolidation of rule-based reasoning, provided that principle-based reasoning is rather rare in the general population (Demetriou and Kyriakides 2006). In fact, examination of school effects on the attainment reflected by the curve in Fig. 3.3 showed that each extra year of schooling accelerates development by the equivalent of 1/3 of the developmental level (Kyriakides and Luyten 2009). Our learning studies summarized here indicated that to cause attainment of principle-based thought requires specific learning programs that are not systematically available in our educational systems.

3.6 Conclusions

There are several important messages in this chapter about human intelligence and its development. First, a general core of mental processes does exist. This may have the functions ascribed to it by classical psychometric or developmental theories. Like g, it underlies mental functioning in every domain. Like developmental structures, it systematically changes through the years, causing all other abilities to improve. However, second, this core is defined differently from psychometric g or developmental common structures. It is thought to involve very general processes which are free of content of any kind, be it inferential or representational. These processes simply allow for search, alignment, abstraction (similization and differentiation), and encoding and reduction (metarepresentation) of information into new meaningful mental units. This is the AACog mechanism. In biological terms, this core is for phenotypically distinct mental processes what DNA is for different body cells or structures. It is everywhere, it can be extracted from everywhere, and it can be used to accurately map any specialized process. This was the meaning of the fact that all ability specific factors proved equally good proxies for a second-order factor standing for AACog.

In development, this core is expressed as a minimal executive control program enabling children to manage cycle-specific representations. Specifically, in the episodic cycle, the program allows the infant to represent and handle episodic action sequences joining attractive environmental stimuli with the infant's actions. In the cycle of realistic representations, the executive program allows the toddler to focus on pairs of representations (e.g. day–night) and map them onto respective responses (e.g. day–dark; night–light) in accordance with a rule indicating that the pairing is under mental control rather than automatic association. This ability is made evident in several achievements of this age group where children connect distinct knowledge states with corresponding representations, as in the theory of mind (Wellman 1992) or appearance–reality distinction tasks (Flavell et al. 1995). In the cycle of rule-based representations, the program allows children to mentally search mental spaces, shift between them, (e.g. say first all fruits coming in your mind, then all furniture, then all animals), and operate on them (e.g. say all round fruits, then four-legged furniture, then two-legged animals). The flexibility in searching representational spaces and aligning them to rules is made evident in n-back or backward-digit span tasks requiring a reorganization of information in WM, scan n-dimensional, Raven-like matrices in order to decipher their relation, or properly arrange problem-solving steps in various mathematical problems. This form of attentional control enables the specification of commonalities of representations and their reduction into a representational token that may be mentally handled as such. This seems to be a prerequisite of inferential control that dominates in the next cycle.

Therefore, it seems that there is a developmental snowball effect in the expansion of the AACog core. That is, there is a functional upgrading of this core in each phase such that newfound processes in each next phase sit on the processes acquired in the previous phase and become integrated with them into a smoothly running whole. Changes occur in two dimensions: the nature of representations that are possible with advancing age and the awareness and ensuing control of representations that are available to the individual. In other words, epigenetic interactions transform the mind into a powerful representational machine capable of creating and using complex abstract representations, in the service of different domains of knowledge. Our training study of deductive reasoning showed that self-awareness of logical schemes is crucial in the creation of abstract logical patterns of inference (Christoforides et al. in press). These results suggest that cognizance and second-order reasoning go together (Zelazo 2004). Thus, each of the four cycles is a dynamic state of functioning at both the mental and the brain level. At the mental level, each state may be characterized in terms of representational priorities and AACog (e.g. inferential) possibilities. Changes in cognitive efficiency and WM reflect, rather than cause, representational and control changes.

Domains of reasoning and knowledge emerge from the functioning of the AACog mechanism because alignment of related items (by nature or the environment) is more likely than alignment of non-related items. Cognizance enables revisiting and revising alignments, strengthening domain-specificity. With development, these core processes are elevated into domain-specific operations, such as mental rotation in spatial reasoning, sorting in categorical reasoning, arithmetic operations in quantitative reasoning, hypothesis testing in causal reasoning, and moral reasoning in social interaction. We showed above that working memory as a storage capacity is not a major factor in transitions. Working memory appears to be a major factor to the extent that it carries reflective and metarepresentational processes in the handling of information and inference (Demetriou et al. submitted). This assumption may highlight why relational complexity may be a factor in the transcription of the core in each cycle to domain-specific programs. According to Halford et al. (1998), relational complexity refers to the minimum number of relations that define a concept. For instance, the relational complexity of transitivity is three dimensions because to conceive of it one must hold in mind two relations (e.g. $A > B$; $B > C$) and map them onto a third relation (A ? C). Thus, relational complexity reflects limitations in combinativity and generativity that may be used to implement the executive core of a cycle into the rules underlying various domains. Examples are the rules of inductive or deductive reasoning (Christoforides et al. in press), algebra in mathematics, hypothesis testing and experimentation in scientific thought, etc.

Cognizance may be called upon to contribute to decision making in concern of the kind of criteria or process needed. Our learning studies showed that reasoning develops when cognizance processes are directly trained to be explicitly handled during inference. The study focusing on learning deductive reasoning showed that awareness of logical schemes, the mapping of each with its logical implications, and their metarepresentation were important for mastering reasoning. The study focusing on mathematics showed that learning may affect the AACog core and parameters of its efficiency, such as WM and attention control. However, both studies showed that there is a ceiling to how far learning gains can go which relates to the representational possibilities of the affected. Obviously, this model has several implications for education (Demetriou et al. 2011) and brain science (Demetriou et al. in press) which are discussed elsewhere.

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