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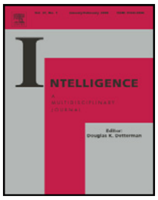

Cycles in speed-working memory-G relations: Towards a developmental–differential theory of the mind[☆]

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ABSTRACT

This article presents three studies, two of them longitudinal, which investigated the relations between age, processing speed, working memory (WM), and fluid intelligence (g_f) from 4 to 16 years of age. Structural equation modeling showed that speed was a powerful covariate of age (~−.6 to −.7) from 4 to 13 years, declining thereafter (to ~−.2). WM was stably related to speed through the whole age-span studied (~−.4 to −.5). A large part (59%) of age-related changes in g_f (83%) from 4 to 7 years and a lower but significant part later on, especially in adolescence (~10–20% out of ~40–50%), were mediated by WM. However, with speed and age controlled, WM was almost fully commensurate with g_f (~.9), from about the age of 8–9 years onwards. A series of models suggested an ever present efficiency level defined by speed and control and a representational level defined by WM and *gf*, which are increasingly differentiated with development. All processes develop in cycles concerted by a dynamic *G*. Change in each process over time originated from within the processes themselves and *G*, in proportions varying with developmental phase. Overall, speed signified age-associated changes in processing capabilities, partly expressed in WM expansions and g_f reconstructions. An overarching model is proposed integrating differential with developmental theories of human intelligence.

1. Introduction

With development there are systematic changes in the ability to understand new information, form new concepts, shift between them, according to changing needs, and solve problems. Developmental theories of the human mind aimed to describe the state of these abilities through the life span and explain when, how, and why they develop (Baldwin, 1894; Case, 1985; Fischer, 1980; James, 1890; Piaget, 1970). Notably, theories of intelligence, which focus on individual differences rather than on development, aimed to describe and explain, when, how, and why individuals differ in these abilities (Carroll, 1993; Hunt, 2011; Jensen, 1998; Spearman, 1904). In this article we try to integrate developmental and differential theories of intelligence into a common theory, drawing on the findings of three empirical studies covering the age span from 4 to 16 years.

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Information processing theories of cognitive development ascribe changes in the abilities above to changes in basic mechanisms underlying information processing and representation (Case, 1985; Demetriou, Christou, Spanoudis, & Platsidou, 2002, 2010; Demetriou, Efklides, & Platsidou, 1993; Demetriou, Mouyi, & Spanoudis, 2010; Halford, Wilson, & Phillips, 1998; Pascual-Leone, 1970). According to these theories, increases in speed of processing enable persons to handle more efficiently information flow during problem solving, because information can be represented, interpreted, and integrated before relevant traces fade away (Hale & Fry, 2000; Kail, 1991, 2000). Increases in working memory enable persons to represent and process more information units at the same time. As a result, they can construct more complex concepts or relations. It is well established in the cognitive developmental literature that increasing processing speed is related to increasing working memory, which in turn is related to ascension to higher levels of cognitive development (Case, 1985; Demetriou et al., 2002; Halford et al., 1998; Pascual-Leone, 1970).

In differential psychology, both speed of processing and working memory were invoked to explain individual differences in general intelligence or *g*. Jensen (1998) suggested that speed of processing is the purest manifestation of *g*, because it reflects the quality of information processing in the brain. Other researchers showed that the relation between fluid intelligence (or g_f), which stands for the abilities mentioned above, and working memory is very strong, suggesting that they share common representational constraints (Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990).

Therefore, there is wide agreement between developmental and individual difference researchers that differences in cognitive ability between successive age phases reflect age differences in speed of processing and working memory and that individual differences in g_f (or IQ, a robust index of g_f) between persons of the same age reflect individual differences in them. This agreement is a good basis for their integration, because these two fields do study the same processes. Research in the high days of Piaget showed that Piagetian tasks and classical tests of intelligence correlate highly (~.6–.8) (Case, Demetriou, Platsidou, & Kazi, 2001; Lautrey, 2002). These findings reflect their common emphasis on inference and problem solving.

Despite this basic agreement, it is still debated if speed or working memory is the most important agent of intellectual development and individual differences. It is even debated which of the components of working memory, mainly short-term storage or executive control, is the most important mediator of effects on developmental or individual differences in intelligence. Some scholars maintained that processing speed is the fundamental source of all changes (Coyle, Pillow, Snyder, & Kochunov, 2011; Hale & Fry, 2000; Kail, 1991). However, others maintained that speeded performance tasks activate attention, which is the actual mediator of the speed–intelligence relation (Stankov & Roberts, 1997). In this line, Engle and colleagues maintained that executive processes in working memory bridge working memory with intelligence (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Conway, Kane, & Engle, 2003; Engle, 2002). Contrary to these findings, however, Colom et al. (2008) showed that neither speed nor executive control in working memory connects information processing with intelligence; only short-term storage does so because they are both constrained by the amount of information that can be temporarily retained and updated.

Differences in findings may arise from any or both of the following reasons. On the one hand, the various information processing functions overlap with each other in a cascade fashion. Demetriou and colleagues (Demetriou, Mouyi, & Spanoudis, 2008; Demetriou et al., 1993, 2002) showed that simpler functions are embedded in more complex functions. Therefore, any one may be shown to relate to intelligence, if they are not disentangled from each other, because of their common features. On the other hand, even when components are carefully separated, disagreements may arise because the relation between these functions and intelligence varies with age. It is interesting that most cognitive developmental theories assume a uniform relation between each of these functions and intelligence. With respect to speed, it is assumed to increase as an exponential function of age from birth to early adulthood, so that different ranges of speed can be associated with the successive levels of intellectual development (Kail, 1991, 2000). In concern to working memory, it is claimed that the successive levels of intellectual development are associated with a particular value of working memory span (Case, 1985; Halford et al., 1998; Pascual-Leone, 1970). However, it may be the case that at some phases of development changes in a particular information processing function may be more important for g_f changes than another one, because the information processing needs of inference differ across phases.

2. The studies

The three studies presented below aimed to answer these questions, because they covered a critical period of development in which all processes change extensively, i.e., from 4 to 16 years of age. Moreover, two of them were longitudinal and thus able to highlight patterns of change as such.

2.1. Questions, modeling, and predictions

2.1.1. Relations between processes

First, we investigated how age, speed of processing, working memory, and g_f are inter-related throughout the age span from 4 to 16 years. To answer this question, three types of structural equation models were tested on the performance attained in each study. The first was based on the model tested by Coyle et al. (2011), which included only measures of speed of processing and g_f. That is, in this model, (i) speed was regressed on age and (ii) g_f was regressed on age and speed (models A in Table 1). The second model included working memory in addition to these factors. That is, in this model, (i) speed was regressed on age, (ii) WM was regressed on age and speed, and (iii) g_f was regressed on age, speed, and WM (models B in Table 1). Thus, the second model, compared to the first, can show how the relations between age, speed, and g_f may change as a result of including WM. This is possible because WM may absorb effects that are specific to it but in the first model were indirectly represented by speed. In the third model, whenever

Table 1
Fit statistics, standardized path coefficients, and mediation effects from structural equation models tested in the longitudinal studies.

	Fit statistics					Age→			Speed/$^{\text{control}}$→		WMrt→			WM→	Age→ effects		
Study	Model/wave	X^2/df	p	CFI	RMSEA	Speed	WM	*gf*	WM	WMrt	*gf*	WM	*gf*	*gf*	Tot	Ind	Z
Study 1																	
4–7	A	18.80/18	.34	.99	.03	−.72*		.75*			−.22*				.91*	.16	1.78
N = 140	B	33.14/32	.41	.99	.02	−.72*	.67*	.15	−.30*		–			.86*	.92*	.77*	2.00
	C	52.63/48	.32	.99	.03	−.75*	.46*	.43	−.52		$–^{-.13}$			.55*	.90*	.47*	2.02
Study 2																	
6–11	A/AW2	37.23/12	.00	.98	.08	−.76*		.54*			−.38*				.82*	.28*	5.46
N = 395	B/W2	85.04/30	.00	.97	.07	−.76*	.18	.47*	−.47*		−.19*			.39*	.82*	.35*	6.51
	C/W2	80.67/48	.00	.98	.04	−.76*	–	.49*	$-.81^{*-}$	.32*		.65*	−.20*	.59*	.81*	.31*	5.95
6–8	B	142.76/100	.00	.96	.04	−.65*	–	.45*	−.51*	−.04	−.32*	.62*	–	.36*	.78*	.33*	4.60
9–11	B					−.45*		.26*	−.65*	.45*	–	.72*	−.25*	.62*	.40*	.14*	2.92
6–7	B	227.22/162	.00	.92	.04	−.42*			−.44*	.10	−.70*	.83*		.40*	.35*	.35*	2.28
8–9	B					−.31*			−.44*	.28*	−.35*	.78*		.58*	.15*	.15*	2.30
10–11	B					−.45*			−.66*	.54*	–	.52*	−.19	.88*	.23*	.23*	3.02
6–8	B	38.24/39	.50	1.0	.00	−.71*		.48*	−.28					.49*	.57*	.10	1.18
9–11	B					−.14			−.44					.64*	.04	.04	.78
Study 3																	
8–14	B/W1	49.50/31	.02	.97	.07	−.74*	.39*	.58*	−.49*		–			.42*	.89*	.31*	3.06
9–15	B/W2	36.78/32	.26	.99	.04	−.69*	.41*	.25	−.51*					.63*	.73*	.49*	2.93
10–16	B/W3	30.78/31	.48	1.0	.00	−.67*	.30*	.28	−.47*					.62*	.67*	.38*	2.84
8–10	B/W1	93.80/70	.03	.91	.06	−.54*		–	−.69*		–			.88*	.33*	.33*	2.63
12–14						−.29	.37*	–	−.36*		–			.58*	.28*	.28*	2.07
9–11	B/W2	78.56/73	.31	.97	.03	−.49*			−.72*					.99*	.35*	.35*	3.05
13–15						−.25	.51*		−.13					.99*	.54*	.54*	3.42
10–12	B/W3	79.35/72	.26	.96	.03	−.50*			−.65*					.79*	.26*	.26*	2.46
14–16						−.17	.68*		−.28					.99*	.73*	.73*	4.08

Note: Values for control are given as superscripts in models C, under the Speed/$^{\text{control}}$ heading, whenever they exist. WMrt stands for reaction times to WM tasks, whenever they exist.

possible, control of attention was differentiated from speed and executive processes in working memory were differentiated from short-term storage to specify if they have any incremental effect on g_f (models C in Table 1). Control-specific factors may absorb effects specific to control that in the models above were indirectly represented by speed and/or WM. These models are shown in Fig. 1 in the conventions of structural equation modeling.

Under these conditions, in line with earlier research, the critical pattern that would contribute to the resolution of

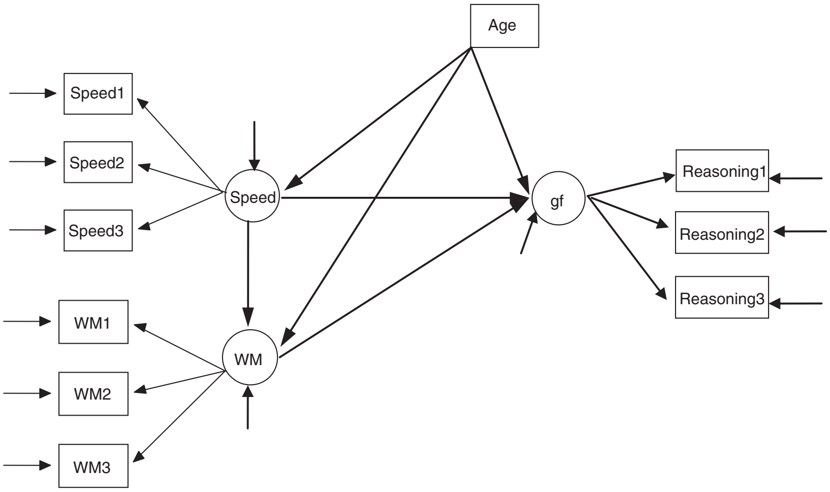


Fig. 1. The general model for testing the structural relations between age, speed, working memory, and *gf*. Working memory was not included in Model A but it was included in Model B. The statistics and structural relations of these models fitted onto the various studies are presented in Table 1.

contradictions noted above would be a strong age–speed–*gf* relation in models A that would be overwritten by working memory when present in models B above (prediction #1). This pattern would highlight the cascade transfer of effects from lower to higher levels of functioning. Moreover, a systematic variation in the strength of relations between processes as a function of age might reveal possible differences in the role of each of them in different phases of intellectual development (prediction #2).

2.1.2. Origins of change

To further zoom in on the role of each process in different phases of development, we investigated longitudinally how different levels in the organization of cognitive abilities contribute to change in actual cognitive performance across time. Three levels were studied here: (i) individual processes (i.e., speed in different types of information, different types of working memory, and different types of reasoning); (ii) systems of processes (i.e., speed, working memory, and g_f); and (iii) *G*, which includes what is common between all three levels.

To answer this question, we employed the modeling approach recently proposed by Salthouse (2011). According to this approach, which requires longitudinal data, the covariance between the test scores obtained for the same process at two testing occasions T1 and T2 is specified in a series of models of increasing hierarchical structure between measures. Specifically, at a first level, test scores are only related to the latent ability-specific factor they are supposedly related to at each testing occasion (i.e., each speed test is related to the speed factor, each working memory test is related to the working memory factor, and each g_f test is related to the g_f factor). No structural relation between factors across testing occasions is imposed. At the second level, each ability-specific factor of a subsequent testing wave is regressed on the corresponding factor of the previous wave. In these models, the covariance between test scores is affected by the structural relations between the constructs across the two testing occasions T1–T2, because the covariance between tests may derive directly from the relation between the factors as such, in addition to covariation coming from within each process. At the third level, the ability-specific factors at each testing wave are related to a higher-order *G* factor and the *G* factor at T2 is regressed on the *G* factor at T1. In these models, the covariance between test scores may also be affected by the structural relation between the *G* factors across the testing occasions, because this relation may affect the covariation between the test scores operating on top of their covariation coming from the effects of the corresponding ability-specific factors.

This relation is shown in Fig. 2. In regard to the overall functioning of the mind, it is hypothesized that changes in abilities at lower levels may come from within the abilities themselves but also from the abilities residing at higher levels. Specifically, any reduction in the covariance between test scores in the second model compared to the first is due to the relation between the ability-specific factors (or possibly *G*) at the two testing waves. Any reduction in the covariance between the test scores in the third model compared to the second is due to the relation between the *G* factors only. Thus, subtracting the covariance of the second model from the covariance of the first model (and dividing by the value of the first wave) shows the percentage of change due to the ability-specific factor (or higher); subtracting the covariance of the third model from that of the first model (and dividing by the first) shows the percentage of variance that is due exclusively to influence of *G*. When the pure ability-specific percentage is subtracted from 1, we obtain the change in the relation between the two occasions that is due to the process (or test) itself.

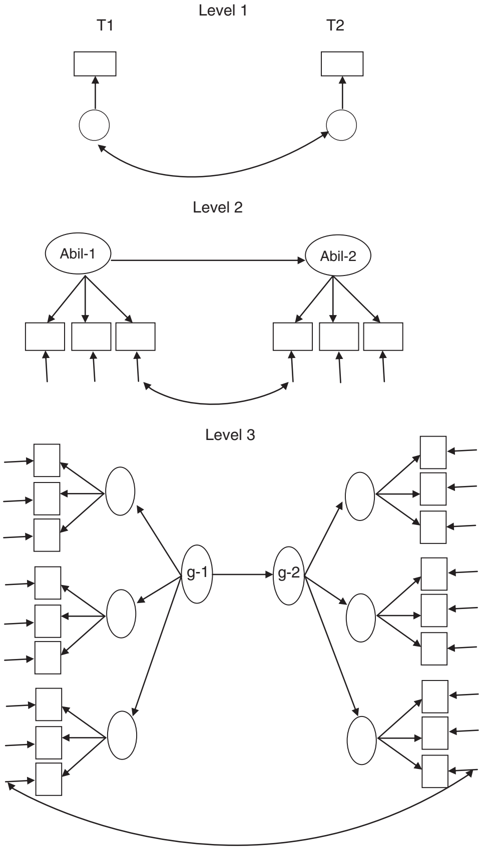


Fig. 2. The general model for testing the effects of three hierarchically distinct levels of structure on change on task performance across successive testing waves. The findings of testing these models on the longitudinal studies are shown in Table 2.

This method is ideal to reveal possible differentiations in the role of each of the processes examined as a function of development. If this is indeed the case, we would expect that the influence of general processes on the change of particular cognitive processes would be stronger in phases of major transitions associated with broad reorganizations of cognitive processes. In periods of consolidation change emanating from within processes may dominate to reflect possible individual differences in the implementation of possibilities in different domains. Moreover, some processes may be more pertinent than others to express general changes in understanding. Speed is obviously one such candidate as a relatively content-free index of functioning (prediction #3).

2.1.3. Stability of structure

One might ask if the organization of cognitive processes remains stable with age. In differential psychology increasing g results in differentiation of cognitive abilities because excessive g allows for investment into domain-specific learning, thereby fostering domain autonomy. This is known as the Spearman's law of diminishing returns for age (SLODRage) (Jensen, 1998; Spearman, 1927). In cognitive developmental theory, inferential power comes with increasing integration of mental operations into logical structures (Case, 1985; Piaget, 1970). To explore what organization is best for different phases of development we contrasted several alternative models which assume different types of relations between processes. It is noted that all of the models discussed above are reductive. That is, they assume that complex processes may be reduced to simpler processes. Reduction at the extreme would espouse identity theory (Smart, 2007). In the present context, identity theory would state that inferential, storage, and processing efficiency processes all depend on the same latent attribute. In SEM terms, according to Kievit et al. (2011), a single-factor model, where all inferential, storage, and information processing measures are regressed on the same factor, would fit the data. This model is illustrated in Fig. 3A.

Alternatively, if simple information processing functions contribute to but they do not themselves fully form the higher level representational and inferential processes, a supervenience model of the relation between processes would fit the data better. According to supervenience theory (Kim, 1985), higher level processes "supervene on lower order properties that *do not necessarily share* all the characteristics that relate to the supervening property" (Kievit et al., 2011, p. 4). In other words, higher level processes include additional elements to those represented by the lower level processes. In the present context, the simplest version of the supervenience model is shown in Fig. 3B. It can be seen that according to this model, all working memory and inference indicators were related to one common factor which was regressed on each of three processing efficiency indicators. A more refined version of this model assumed two factors, one for working memory and one for inference, that may or may not correlate (Fig. 3C) with each other. Each of these two factors was regressed on the processing efficiency indicators. A fully supervenient model would assume three levels, one for processing efficiency, one for WM, and one for reasoning, each represented by a separate factor regressed on the respective set of indicators. In turn, each of these factors was regressed on all three indicators residing at the lower level. Thus, effects in this model ascent from each lower level to the next higher level (Berkman & Lieberman, 2011). This is the model illustrated in Fig. 3D. Differential theory would predict that cognitive processes tend to differentiate in more specific abilities (prediction #4a). Cognitive developmental theory would predict that, with increasing age, cognitive processes tend to get organized in more inclusive structures (prediction #4b).

3. Study 1: from early to middle childhood

This study focused on early childhood. It involved 4- and 5-year old preschool children and first and second grade primary school children. These children were examined by tasks addressed to all of the processes mentioned. That is, speed and control of processing, short-term and working memory, and g_f. The g_f tasks addressed inductive and deductive reasoning in the domain of categorical, quantitative, and spatial relations. The tasks were especially designed for this early phase of development.

3.1. Participants

A total of 140 children were examined. There were 38 4-, (m age: 4.2), 32 5- (m age: 5.2), 34 6- (m age 6.2), and 36 7-year old children (m age: 7.4). Genders were about equally represented in each age group. All children lived in Athens and came primarily from middle-class families.

3.2. Tasks

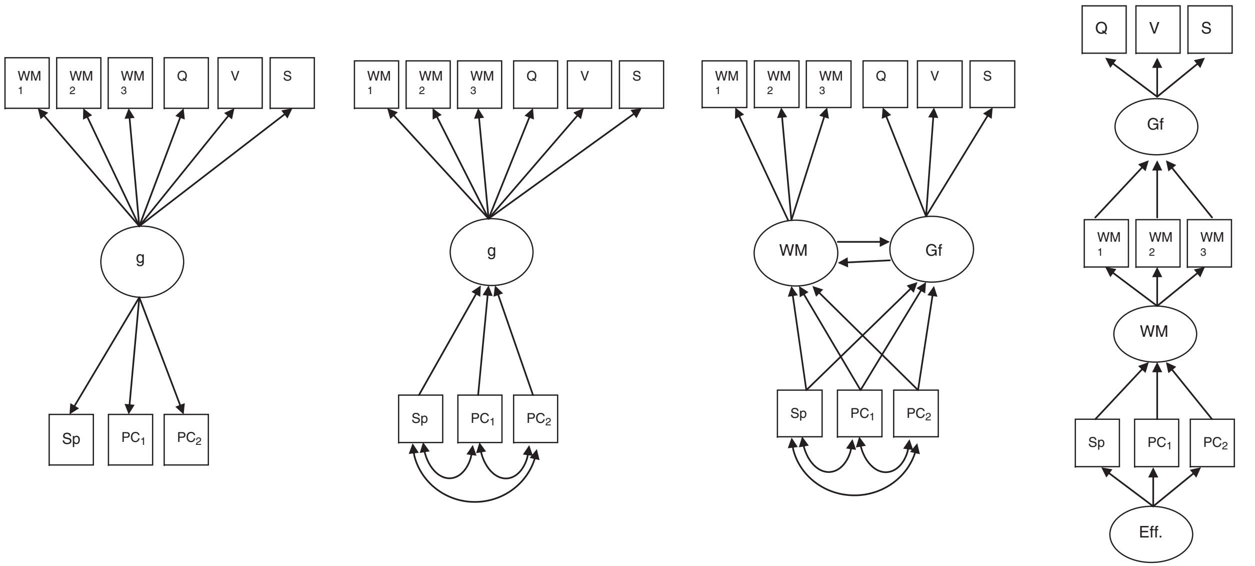
3.2.1. Speed and control of processing

To test speed of processing, children were presented pairs of items presumably associated with categorical, quantitative, and spatial thought. Pairs of objects (e.g., gloves), dot arrangements, and geometrical figures (e.g. triangles) addressed the three domains, respectively. The items in each pair were simultaneously presented, one on the left and the other on the right side of the screen and children were asked to indicate if they were similar or different by choosing the corresponding key on a SR box. There were three levels of similarity: identical, similar (same objects slightly differing in appearance), and different. Reactions to similar items were taken as measures of speed of processing. Reactions to different items were taken as measures of control.

Three stimuli were used for each of the two dimensions of the processing system (i.e., speed and control of processing) for each of the three symbol systems. To avoid random responses, only correct reactions were included in the analysis and a mean was estimated for speed and control only when two of the three responses in each set were correct. Moreover, reactions faster than 500 ms and/or longer than 5000 ms were automatically excluded (alpha reliability = .97). This is a common practice in this type of research aiming to ensure that the responses analyzed are relevant to the task (Jensen, 2006). Moreover, the 4-year-olds were screened for inclusion in the study on the basis of their performance on a Simon speed task. Specifically, only children succeeding on at least 70% of the trials on this task were retained for further testing (49% of 4-year-old children). Screening was necessary for this age because pilot examinations showed that about 50% of this age group tended to respond randomly to speeded performance tasks. Therefore, this screening ensured that the youngest children included in the study were matched to the older children on their ability to respond reliably. No older child was dropped based on this criterion.

3.2.2. Working memory

Three tasks addressed working memory. The Corsi block task addressed visuo-spatial memory. A 16 × 16 squares layout was shown on screen; a cartoon stepped randomly in several of these squares. To test working memory, children were asked to recall these squares in reverse order. The memory demand ranged from one to seven cartoon appearances. To test phonological short-term storage, 34 familiar two-syllable words and 34 two-syllable pseudo-words sounding like proper words were used. Children recalled the words in presentation



A. 1-level 1-factor Identity model. All CFIs < .91 and all RMSEAs > .11.

B. 2-level 1-factor supervenience model. Best for 4-7 years ($\chi^2(24)=67.53$, p=.00, CFI=.97, RMSEA=.07.

C. 2-level 2-factor supervenience model. Best for 7-11 years ($\chi^2(20)=47.95$, p=.06, CFI=.98, RMSEA=.06.

D. 3-level 3-factor supervenience model. Best for 9-15 years ($\chi^2(21)=26.27$, p=.20, CFI=.98, RMSEA=.05.

Fig. 3. The identity (A) and supervenience models (B–D) tested on Studies 1–3. The symbols WM1–3 stand for the three WM tasks used in each study. The symbols Q, V, and S stand for quantitative, verbal, and spatial reasoning, respectively. The symbols Sp, and PC1–2 stand for speed and control as examined in the three studies, respectively. The fit indices and coefficients of all models are shown in Table 5A in Appendix A.

order. Difficulty ranged from 1 to 5 words. Scores equaled the higher level attained on each task (alpha reliability = .56).

3.2.3. gf

Cognitive tests addressed quantitative, spatial, deductive reasoning, and analogical reasoning. Specifically, counting from 3 to 9 objects and three arithmetic operations tasks (i.e., $1+2$, $2+3$, and $7+4$) addressed quantitative reasoning. It might be objected here that object counting does not address *gf*. However, before automated, counting would require *gf* because children must properly coordinate the number name sequence with object pointing. This ability is constructed in the 3–6 year period (Leslie, Gelman, & Gallistell, 2008). Therefore, counting was used as an index of the lower end of fluid abilities of this age phase. The arithmetic operations tasks were enacted by the experimenter, who placed as many cubes as required in a box (e.g., she first placed 2 and then 3 cubes in an empty box), and called the child to specify the number of cubes in the box. One point was given for each correct answer.

For spatial reasoning, children assembled puzzle-like model figures. Children were presented with a model figure (i.e., a house), and they were asked to reproduce it on the side, by properly arranging its component parts (i.e., a square, a triangle, and a semicircle). Difficulty varied with the number (3–5), shape, and rotation of the components involved. Scoring ranged from 0 to 2 to reflect mastery of the ability to compose a figure by properly arranging and rotating its parts.

Deductive reasoning tasks involved mapping simple permission rules onto their relevant pictorial representation. Modus ponens, negation of modus ponens, conjunction, and disjunction arguments were given (e.g., “If Ann wants to ride her bicycle, she must put her sneakers on”) and children chose a picture among others that they thought was consistent with the argument (e.g., Ann with and Ann without her sneakers on) and explained their answer. Scoring ranged from 0 to 3 and reflected the ability to grasp the logical relations involved accordingly.

Analogical reasoning tasks addressed quantitative, spatial, and categorical relations. In the quantitative task, children saw two sticks, each involving a different proportion of white and red sections (i.e., 1 to 3 vs. 3 to 1; 3 to 3 vs. 3 to 2; and 2 to 1 vs. 3 to 2 red and white sections, for tasks 1, 2, and 3, respectively) and chose which of them had more red sections compared to white sections, and then explained their answer. In the spatial analogical reasoning task, children indicated which of three figures divided in two sections matched a target figure divided in two sections according to a specific ratio. The categorical analogical reasoning task addressed categorical relations between objects and classes in the standard verbal analogy format where children chose the missing term (e.g., bird:nest::dog:? (*dog-house*, dog, cat, bone; correct answer in italics)). Scores ranged from 0 to 3 to indicate advancing understanding of relations within and between pairs (alpha reliability = .86).

3.3. Results and discussion

3.3.1. Explaining change in gf

Table 1 shows the model fit, the structural relations between constructs, and the total and indirect effects of age on g_f (the correlations, means, sd for this models are shown in Table 1A in Appendix A). It can be seen that the fit of all three models was excellent. The relation between speed and age was very high in all of them (>.7). In the first model, the relation of g_f with age (.75) was high but the relation with speed (−.22) was low. However, when WM was included in the model, the relation between g_f and age or speed dropped drastically. Introducing control did not differentiate these relations and the relation between control and g_f was very low (−.13). Obviously, the very strong g_f–WM relation (.86) absorbed the g_f–speed relation. The relation of WM with speed was moderate (−.30). It is interesting that in this period of development, the total effect of age on g_f was very high (.91, 83% of the variance). A considerable part of this effect was indirect and significant, coming almost entirely from WM (.77, 59% of the variance) in the second model as contrasted to the first model (.16, 3% of the variance). Therefore, patterns of relations between processes were consistent with prediction #1 in the age period covered by this study.

3.3.2. Structure

The one-factor supervenient model (CFI = .965, RMSEA = .071) fit best in the age period from 4 to 7 years covered by this study (Fig. 3B). The fit of both the single factor model implementing identity theory (Fig. 3A) and the more refined supervenience models (Fig. 3C and D; see fit indices in Fig. 3) was very poor. Therefore, in this age period the mind appeared to operate in two organizational levels: the functional level represented by processing efficiency functions and the representational level represented by working memory and inferential processes. We stress the lack of differentiation between working memory and inferential processes.

4. Study 2: middle childhood

This study involved children from the first to the sixth primary school grade. This study used a large number of tasks addressed to various aspects of speed and control of processing, working memory, and deductive and inductive reasoning. Some of the participants involved in this study were tested two times.

4.1. Participants

The main sample of this study included 395 children, about equally distributed between the six primary school grades. Specifically, there were 62, 62, 75, 68, 54, and 74 participants from first through sixth grade, respectively. The mean age at the first testing was 6.7, 7.9, 8.9, 9.8, 10.7, and 11.7 years, respectively. About one third of the children in each grade were tested twice, separated by 12 months (i.e., 23, 24, 22, 21, 25, and 25 from first through sixth grade, respectively; a total of 111). Genders were about equally represented in each grade. These children came from middle-class families living in Nicosia, the capital of Cyprus.

4.2. Tasks

4.2.1. Speed and control of processing

A Stroop-like paradigm was employed to test speed and control of processing in three symbol systems: verbal, numerical, and figural. That is, for speed of processing in the verbal system, the participants were required to read single words written in the same ink color (e.g., RED in red ink, say red). For control of processing in this system, the participants were required to recognize the ink color of color words denoting a different color (e.g., RED in green ink, say green). For speed of processing in the numerical system, the participants were required to recognize "large" number digits composed of the same digit (e.g., 7 composed of little 7 s, say 7). For control of processing in this system, the participants were required to recognize the small component digit of which the large ones were composed (e.g., 7 composed of 4 s, say 4). For speed of processing in the figural system, the participants were required to recognize "large" geometrical figures composed of the same figures (e.g., a circle composed of circles, say circle). For control of processing in this system, the participants were required to recognize the small component figures composing the large figure (e.g., a circle composed of triangles, say triangle). Two stimuli were used for each of the two dimensions of the processing system (i.e., speed and control of processing) for each of the three symbol systems. Reaction times to all three types of the compatible conditions described above indicate speed of processing and reaction times to the incompatible conditions indicate control of interference in processing (Demetriou et al., 1993, 2002; Jensen, 1998; Stroop, 1935). Cronbach's alpha was high (.96).

4.2.2. Visuo-spatial working memory

To test visuo-spatial memory, a total of eight arrangements of geometrical figures of varying complexity were presented to the participants. Specifically, of this total, two arrangements involved two figures, two arrangements involved three figures, and the other four arrangements involved four, five, six, and seven figures, respectively. Each of the arrangements was presented for as many seconds as the number of figures in it. Four alternative arrangements were presented immediately after the presentation of the target arrangement and the participant was asked to identify the correct one.

4.2.3. Numerical working memory

Two tasks were patterned on Case (1985) and addressed working memory. Both tasks involved seven levels of difficulty. Each level was defined by the number of items to be stored in memory. In the first task, in each level, a set of number digits, differently colored, were presented in succession for 2 s each. At the end of the presentation of each set, a target digit was presented and the participant's task was to specify if this target digit was bigger than the same color digit included in the set. Four trials were given for each level of difficulty. Participants had to succeed in at least two of the four trials in order to move on to the next level.

4.2.4. Numerical–visual working memory

The second task was identical to the first in all respects, but the numerical information presentation involved in each trial. That is, instead of number digits, the numbers were represented by dots of equal size. Participants were instructed to keep in memory both the numerical information and the color of the items presented in each trial. Following Case (1985), participants were credited with a level if they succeeded on half or more of the items addressed to this level. The maximum score was 5 for the visuo-spatial task and 7 for the numerical tasks (alpha reliability = .51).

All working memory tasks were computer administered. Children were instructed to recall the relevant items as carefully and fully as possible. Their reaction times to all items were automatically recorded.

4.2.5. Reasoning

A long battery of tasks addressed inductive and deductive reasoning through tasks involving verbal, mathematical, and spatial relations.

A total of 38 items addressed inductive reasoning. Specifically, there were 12 verbal inductive reasoning tasks, five syllogisms and seven verbal analogies. The syllogisms required one to make an induction about a particular case in a story based on the characteristics of a group of cases. A point was given for each right choice. In the verbal analogies one of the four components was missing and participants chose the right answer among four alternatives. One point was given for each right answer. Difficulty was controlled in reference to the familiarity and abstractness of the relations involved.

In the same fashion, there were seven inductive syllogisms involving numbers and six involving numerical analogies. In the number syllogisms, participants were required to make inductions for the composition of a particular number based on information about the composition of a set of similar even numbers (e.g., even numbers can be divided into two equal halves). In the mathematical analogies, the children chose the missing number of a pair based on the relation between a complete pair. Difficulty was controlled on the basis of the relation involved (e.g., double, triple, $2x+1$).

Finally, six spatial syllogisms addressed the ability to extract a general rule underlying the movement of a worm in the various squares of a rectangular matrix, according to a particular pattern. Complexity varied as a function of both the size of the matrix (there were two 5×5, two 7×7, and two 11×11 matrices) and the pattern of movement in the matrix (i.e., the number and the direction of turns required). Seven a:b::c:d Raven-like matrices were addressed (color, shape, and transformation).

A total of 30 items addressed deductive reasoning in the verbal, the mathematical, and the spatial reasoning domain. Sixteen standard arguments addressed verbal propositional reasoning. These arguments involved two premises and a conclusion and the participant's task was to indicate whether the conclusion was right, wrong, or undecidable. Arguments addressed: modus ponens (i.e., if p then q, p, therefore q; 4 items); modus tolens (i.e., if p then q, not q, therefore not p; 4 items); the fallacy of affirming the consequent (i.e., if p then q, q, therefore no logically correct conclusion can be reached; 4 items); and the fallacy of denying the antecedent (i.e., if p then q, not p, therefore no logically correct conclusion can be reached; 4 items).

Seven tasks addressed deductive reasoning involving mathematical relations. Participants were asked to specify the number digits (0–9) to be placed in three or four boxes, drawn side by side, based on a set of propositions constraining each other. Difficulty was controlled in reference to the number of digits to be specified (four problems involved three and three problems involved four digits), the number of propositions involved (three 3-digit problems involved five propositions and one involved six propositions; of the 4-digit problems, one involved seven, one involved eight, and one involved nine propositions), and the logical relations involved in the propositions.

Finally, seven tasks addressed deductive reasoning involving spatial relations. The structure of these tasks was similar to the structure of the tasks above involving mathematical relations. That is, participants were asked to specify the position of a number of animals or persons sitting next to each other based on the information of a number of propositions constraining each other in the fashion of the mathematical reasoning tasks described above. Tasks involving three, four, five, six, seven, and eight persons were used. Two, three, four, five, and eight propositions were involved. One point was given when all names were correctly placed on the diagram (alpha reliability = .84).

Two composite scores were formed based on the nine observed variables used in the reasoning test. Specifically, the score for inductive reasoning was the mean score of the six inductive reasoning tests and the score for deductive reasoning was the mean score of the three deductive reasoning tests.

4.3. Results and discussion

It is noted that the models to be presented below are based on the large sample of 395 children tested at the second testing wave. Some models are based on the sub-sample of children that were tested twice (the correlations, means, sd for this models are shown in Table 2A1–A2 in Appendix A).

4.3.1. Explaining change in g_f

It can be seen in Table 1 that the fit of most models was excellent. The relations between the various constructs were similar to those of Study 1 in some respects but very different in some other respects. The relation between speed and age was equally high in all models that were fit on the whole sample (.76). Attention is drawn to the weaker relation between working memory and age (.18). However, the relation of g_f with age was higher (~.5). Also, the relation of working memory with speed (−.47 and −.81 in the first and the second model, respectively) was considerably higher than in Study 1. As in Study 1, the relation between speed and working memory, although relatively low (−.19) was significant in the first model. However, following the Langrange test for dropping parameters that do not significantly contribute to model fit (see Bentler, 1992), it was dropped when working memory was introduced into the second model. It is stressed, however, that the relation between g_f and working memory was considerably lower in this study (.39) as compared to Study 1 (.86). Interestingly, the relation between working memory and the time taken to respond to the working memory tasks was high and positive (.65), suggesting that higher working memory performance was associated with slower response time. However, working memory reaction time (Mrt) was negatively and significantly related to g_f (−.20). This combination of relations signifies a delicate efficiency balance in the trade-off of speed with the important aspects of actual cognitive performance, which will be discussed below.

According to prediction #2 relations may vary in different periods of development. To test this prediction, we ran the complete model in a 2-group set-up. The first group included the 6-, 7-, and 8-year-olds (199 participants) and the second group included the 9-, 10-, and 11-year-olds (196 participants). Indeed, there were some interesting differences between these two age phases. On the one hand, the relation of speed and g_f with age in the younger age group (−.65 and .45, respectively) was much higher than in the older age group (−.45 and 26, respectively). On the other hand, all other relations were much higher in the older group. Most notable is the relation between g_f and working memory (.36 vs. .62 for the two age groups, respectively) and the relation between g_f and the reaction time to the working tasks (0 vs. −.25, respectively). These are precisely the patterns predicted according to prediction # 2.

In the model fit on the longitudinal data, we used the speed and the working memory scores of the first testing wave and the g_f scores of the second testing wave. That is, in the first group, speed and WM at 6, 7, or 8 are used to predict g_f at 7, 8, and 9 years. In the second group, speed and working memory at 9 or 10 are used to predict g_f at 10 or 11 years. To test the assumption that the structure of abilities does not vary with time but their relations might vary, we constrained all relations between measures and factors to be equal across the two groups and we let the structural relations vary freely. It is recognized that the relatively small number of participants in the two age blocks compared may weaken the statistical power of structural relations. To compensate for this problem the number of measurement in these models was kept to a minimum.

The fit of this model was excellent (see Table 1). The relations between constructs are patterned as expected. In the younger age group, the relations between age and speed (−.71), and g_f (.48) were significant and much higher than in the older age group (−.14 and 0, respectively). However, the relations between working memory and speed and working memory and g_f were much higher in the older (−.44 and .64) than in the younger age group (−.28 and .49, respectively). Thus, it seemed that in the first phase speed reflected age changes because in this phase children became extensively faster in processing and relatively better in *gf*. In the next phase, *gf* changes converged increasingly with working memory, reflecting an across the board expansion of thought towards the capacity indexed by WM.

The pattern of total and indirect effects of age on g_f are very informative about the developmental changes taking place in the age period examined by this study as compared to the earlier period covered by Study 1. Specifically, in the whole sample, the total effect of age on g_f was also very high (.82, accounting for 67% of the total g_f variance). However, in this study, the indirect effect was much lower than in the first study (.35, accounting for 12% of the total g_f variance). This effect was mediated mainly by working memory as speed and control contributed only 4%. It is noted, however, that both the total (.78 vs. .40 for the younger and the older group, respectively) and the indirect effects of age (.33 vs. 14, respectively) on g_f were much higher in the younger age group. This pattern of differences suggests that g_f changes in the period from 6 to 8 are more predictable from age differences and, in turn, these are primarily mediated by speed. In the phase from 9 to 11 there are more degrees of freedom in mental constructions and these are mainly mediated by working memory.

4.3.2. Specifying the origins of change

Table 2 shows the origins of change in the various processes from the first to the second testing wave, according to the analysis of residual covariances. Overall, change seemed to have come from both the processes themselves and *G*. Change coming from *g* was very high in the case of speed (79%), high in the case of reasoning (54%) and moderate in the case of working memory (36%). It is notable, however, that the role of *G* in the change of other processes varied extensively, according to developmental phase and process. Specifically, change in speed came mainly from *G* in the 6–8 year phase (74%) but almost completely from within it in the 9–10 year phase (95%). The same trend was observed in concern to working memory and reasoning. In the two age phases, it dropped from 56% to 25% for working memory and from 88% to 46% for reasoning, respectively. Also, it is to be noted that change in some processes was more specific to them than in other processes. Specifically, change in visual working memory was completely emanating from within itself in both age groups (.99). However, change in working memory was mainly emanating from *G* (.68 in the 6 to 8-year-old age group and .74 in the 9 to 10-year-old age group). Also, change in inductive reasoning was driven by *G* in both age groups (1.0 and .67 in the two age groups, respectively), but change in deductive reasoning was process-specific in both age groups (.75 in both).

Table 2
Estimates of the proportional contributions of three levels of cognitive ability (*G* level, influences unique to the ability level, and test-specific level) to the covariances for tests representing various abilities. The contributions of the three levels are presented in relation to age and testing wave. In Study 2 the three waves were included in the same model. Factors in the first test-specific level were regressed on age, factors in the second, ability specific level, were regressed on the corresponding factor of the previous testing wave and the factors of the first wave were regressed on age. In the third, *G*-specific level, each *G* factor was regressed on the *G* factor of the previous testing wave and the *G* factor of the first wave was regressed on age. Also, the ability-specific factors of the second and the third wave were regressed on the residuals of the previous wave.

Ability	Wave	Age	Process	Ability	G
Study 2	1, 2				
Speed		6.5–11.5	.208	.000	.792
		6–8	.161	.064	.744
		9–10	.945	.000	.055
WM		6.5–11.5	.366	.278	.357
		6–8	.380	.059	.561
		9–10	.753	.000	.247
Visual STS		6–8	.999	.000	.001
WM			.320	.451	.680
Visual STS		9–10	.999	.000	.001
WM			.260	.000	.740
Reasoning (*gf*)		6.5–11.5	.334	.125	.541
		6–8	.125	.000	.875
		9–10	.542	.000	.458
Inductive		6–8	.000	.000	1.000
Deductive			.750	.000	.250
Inductive		9–10	.330	.000	.670
Deductive			.750	.000	.250
Study 3	1, 2, 3				
Speed	1, 2	8-10-12-14	.522	.067	.411
	2, 3	9-11-13-15	.333	.000	.667
	1, 2	8–10	.682	.000	.318
	2, 3	9–11	.267	.289	.444
	1, 2	12–14	.556	.000	.444
	2, 3	13–15	.667	.167	.167
WM	1, 2	8-10-12-14	.594	.201	.254
	2, 3	9-11-13-15	.615	.082	.304
	1, 2	8–10	.622	.022	.356
	2, 3	9–11	.702	.018	.280
	1, 2	12–14	.664	.172	.165
	2, 3	13–15	.704	.000	.348
Reasoning (*gf*)	1, 2	8-10-12-14	.821	.028	.171
	2, 3	9-11-13-15	.547	.024	.429
	1, 2	8–10	.474	.250	.276
	2, 3	9–11	.484	.035	.481
	1, 2	12–14	.516	.294	.190
	2, 3	13–15	.595	.091	.348

4.3.3. Structure

The single factor identity model did not fit performance in this age period as well. However, in this age period, the 2-level 2-factor supervenience model (Fig. 3C) fit better than both the 2-level 1-factor supervenience (Fig. 3B) model and the 3-level 3-factor hierarchical supervenience model (Fig. 3D). Therefore, in this phase, memory processes are differentiated from but correlated with inferential processes. Attention is drawn to the fact that the direction of effects between WM and *gf* may go either way without affecting the model fit at all. In fact, the regression of WM on *gf* (.83) was higher than the classical regression of *gf* on WM (.54), suggesting a reciprocal rather than a one way relation. We will elaborate on these findings in General discussion.

5. Study 3: from childhood to adolescence

This is a three-year longitudinal study that covers the period from middle childhood to middle adolescence. It involved a wide range of tasks addressed to all of the processes examined by the first two studies. Therefore, this study can show how the various relations of interest evolve at the transition from childhood to adolescence and how they settle during adolescence.

5.1. Participants

A total of 113 participants were tested longitudinally three times, separated by 12 month intervals. At the first testing wave, they were at third (m age: 8.1), fifth (m age: 10.1), seventh (m age: 12.1), and ninth grade of compulsory education (m age: 14.1). The two genders were about equally represented in all groups. They came from middle-class families living in Thessaloniki, the second largest city in Greece.

5.2. Tasks

5.2.1. Speed and control of processing

The tasks addressing these processes were identical to the corresponding tasks used in Study 2 (alpha reliability = .95).

5.2.2. Short-term and working memory

Four tasks addressed phonological and visuo/spatial short-term storage (STS). The phonological STS was addressed by two verbal and two numerical tasks. Participants were presented with a series of words or numbers (from two to seven) and they were asked to recall them in the order of presentation. The two tasks in each set were differentiated according to the complexity of the words (i.e., presented in the nominal vs. other cases) or the number digits (i.e., tens vs. two digit numbers where tens and units differed) involved. The visuo/spatial STS was addressed by a task requiring to store shape, position, and orientation of geometric figures. Participants were presented sets of geometrical figures and were asked to fully reproduce them by choosing the appropriate figures among several ready-made cardboard geometrical figures that were identical in size and shape to the figures drawn on the target card.

Working memory was addressed by a set of tasks requiring one to combine either verbal with numerical or verbal with visual information during storage and recall. For example, in the verbal/numerical task, participants were presented with verbal statements comprised of a subject, a verb, a numerical specification, and an object (e.g., "The man ate three apples"; "The father bought two loaves of bread", "The boy has seven balls"). Once all of the statements (from 2 to 7) in a set were presented, the participant was trained to recall either the subject or the numerical specification of all of the propositions in the set, as a response to the instruction WHO or HOW MANY, respectively. Again, there were two variants for each series in each of the two sets. In the verbal/visual task participants were presented with a series of color words (i.e., green, yellow, and blue) written in the same or a different ink color (from 2 to 7 words). In the fashion of the verbal/numerical task above, participants were asked to store both the word and the ink color and recall either the one or the other upon the completion of a set, following the instruction at the end (WORD or COLOR). The score for each task equaled the number of items at the highest level (i.e., 2–7) recalled (Cronbach's alpha = .84).

5.2.3. Reasoning

The cognitive tasks addressed verbal, quantitative, and spatial reasoning. Verbal reasoning was addressed by four verbal analogies as in Study 2 and four syllogisms, two addressing propositional reasoning (modus ponens and denying the antecedent) and two addressing transitivity. Quantitative reasoning was addressed by six numerical analogies (e.g., 6:8::9:?) and four tasks requiring to specify the arithmetic operations missing from simple arithmetic equations (e.g., [2#4]@2 = 6). Spatial reasoning was addressed by six mental rotation tasks (i.e., the participant was asked to draw how several geometrical figures would look like if rotated by 45°, 90°, and 135°) and two water-level tasks (i.e., a picture of a half-full bottle was presented and the subject's task was to draw the line indicating the water level when the bottle is to be inclined first by 45° and then 90°). Tasks in each set varied systematically in difficulty. All items were scored on a pass–fail basis (0 and 1) (Cronbach's alpha = .87).

5.3. Results and discussion

5.3.1. Explaining change in g_f

The models were first fit on the performance attained by the whole sample at each testing wave (the correlations, means, sd for this models are shown in Table 3A1–A3 in Appendix A). Inspection of Table 1 suggests that the relation of speed with age was similar to the previous studies (~.7). The relation of WM with age at the first (.39) and the second testing wave (.41) was higher than at the third wave (.30). The relation of g_f with age was high at the first wave (.58) but considerably lower at the next two waves (.25 and .28, respectively). The total effects of age on g_f also followed this decreasing trend, starting very high (.89, 79% of variance) and ending considerably lower (.67, 45% of variance). On the other hand, the relation of WM with g_f started relatively low (.42) but it stabilized much higher thereafter (.63 and .62 at waves 2 and 3, respectively).

To test the possible differentiation of the patterns of relations with age, as in Study 2, we split the present sample into two groups, the first including the 8- and the 10-year-olds and the second including the 12- and the 14-year-olds. These two groups were included into a multiple group analysis where Model B was tested. In this analysis, all relations between measurements and factors were constrained to be equal across the two groups but the structural relations between the factors were allowed to vary freely. It can be seen in Table 1 that the fit of this model was adequate in all testing waves. Some differences between these two groups are very interesting. First, the pattern of very high g_f–WM relations, which is well known by now, was found again in these models. Moreover, the transition–consolidation effect was present here as well. Specifically, the g_f–WM relation increased as age moved closer to a consolidation phase (.88 and .99 for the periods 8–10 and 9–11 years, respectively) and decreased as it moved away (.79 in the 10–12 period of the first group). Also, in the second group, it increased from .58 in the 12–14 age period to .99 in both the 13–15 and 14–16 periods, signifying that when thought development is complete WM is becoming practically equivalent to g_f, as found by many others (Colom et al., 2008; Kyllonen & Christal, 1990).

It is noted that a series of analyses were run to separate the effects of control from speed and also executive processes in working memory from short-term storage. In all of these analyses, none of these factors added any significant amount of explained variance in g_f. An explanation of this finding will be given in the discussion.

5.3.2. Specifying the origins of change

Results comparable to Study 2 were obtained here. Specifically, change came from within the various processes rather than from *G*, although these effects varied with ability and time. Attention is drawn to the opposite trends in speed compared to working memory and reasoning: In the 12 to 14-year age group, the change in speed coming from *G* dropped from 44% to 17% from the first to the second testing interval. However, it increased from 16% to 35% in working memory and from 19% to 35% in g_f, in the same age period. Despite these variations in the impact of *G* on change, it is stressed that change came primarily from within processes. In fact, in some processes, such as visual memory or spatial reasoning, change was largely process driven (~.7).

5.3.3. Structure

In adolescence, both the 2-level 2-factor (Fig. 3C) and the 3-level 3-factor hierarchical supervenience model (Fig. 3D) appeared to fit performance well. It is notable that the 3-level 3-factor model fit best at the second testing covering the 9–15 year period and the 2-level 2-factor model to dominate at the third testing, covering the 10–16 year period. This pattern indicates that after their differentiation in the primary school years, inferential processes tend to be lifted and supervene over working memory processes in adolescence. As in Study 2, the direction of effects may go either way in the 2-level 2-factor model (.64 and .72 for the WM → *gf* and the *gf* → WM regression, respectively), without affecting the model fit.

6. Integrating across studies

So far, development and relations between processes were examined within the age limits of each study. It would be conducive to the aims of this article to have an integrated picture of the development and inter-relations of the various processes throughout the age span from 4 to 16 years. In this sake, we created a common pool of 662 participants by pulling together the samples of all three studies on the basis of tasks that were identical or very similar. Specifically, we used the speed of processing tasks that required stimulus recognition to stand for speed of processing and the phonological storage tasks to stand for working memory. To obtain an integrated measure of *gf*, Rasch scaling analysis was applied on the performance attained on all cognitive tasks in the four studies. To integrate the three studies the scale was anchored on a number of items which addressed the same cognitive processes (i.e., 4 items from verbal, 3 from quantitative, and 3 from spatial reasoning) and were shown by preliminary analysis to have the same difficulty. This analysis produced a logit score for each participant which stands for her or his overall *gf* attainment.

6.1. Developmental forms

Fig. 4 summarizes the main patterns of results across the three studies. Specifically, panel A of Fig. 4 shows mean speed, working memory, and g_f as a function of age. Panel B summarizes the structural relations between these processes. A univariate ANOVA applied on each of these systems uncovered highly significant and strong age effects on speed ($F_{12,\ 646} = 57.82$, $\eta^2 = .52$), working memory ($F_{12,\ 662} = 14.76$, $\eta^2 = .21$), and g_f ($F_{12,\ 649} = 218.68$, $\eta^2 = .80$), suggesting that all three systems changed systematically with age. Overall, the development of each of these systems may be described as follows.

6.1.1. Speed

In the period from 4 to 6, change in speed was unstable, as mean reaction times wavered around 1.5 s. This instability probably reflected variations in attentional and response handling strategies in this early phase of development. However, from the age of 6 to 7, change in speed became very systematic throughout the years until early adulthood. That is, reaction times dropped from 1.66 s at 7 years to about .65 s at the age of 23 years (see Fig. 4). It seems that in this long period there were two phases of major change in speed: 7–8 and 11–12 years of age, when there was a large decrease of reaction times, and a period of smaller change at 15–16. Thus, there were two plateaus in this development, from 9 to 11 and from 13 to 15 years of age. These results are fully in line with the pattern of change observed by other researchers (Kail, 1991; Kail & Ferrer, 2007).

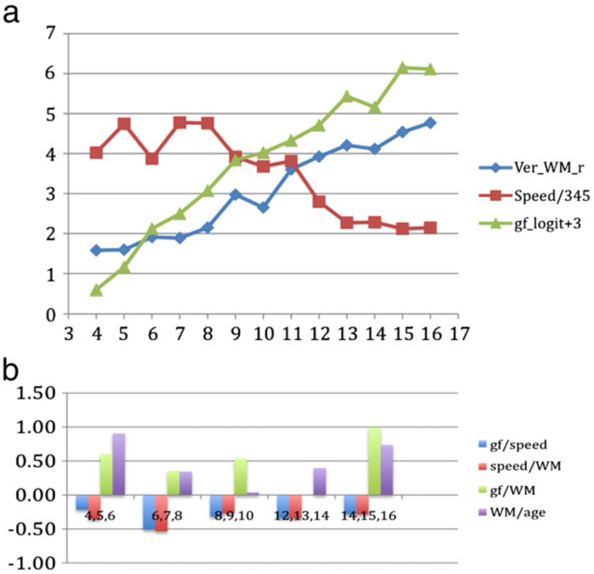


Fig. 4. Panel A shows the speed, working memory, and *gf* (expressed in logit scores) as a function of age. To align the three graphs, speed was divided by 345 and *gf* was increased by 3. Panel B shows the structural relations among these functions and WM and age (taken from models where age groups were organized as shown in the panel).

6.1.2. Working memory

Storage capacity rose systematically from about 1.5 chunks at 4 years to about 5–6 chunks at 16 years, with one spurt starting again at 7 years, when it rose from 2 to 3 chunks, another starting at 10–11 years, when it rose from about 3 to 4 chunks, and another at 15–16 years, when it approached 5 chunks. Overall, the values obtained here are comparable to the values obtained by other researchers of working memory development (Halford et al., 1998; Pascual-Leone, 1970).

6.1.3. Reasoning (gf)

Interestingly, change in g_f as reflected in logit scores was an almost linear function of age throughout the period from 4 (−2.4 logits) to 13 years (2.4 logits), with possible major transitions from 6 to 8 and from 11 to 13 years. This variation in logit scores seems to reflect interesting changes in the nature and organization of representations from 4 to 16, which enrich our understanding of intellectual possibilities at different phases. The full explication of this developmental course is presented elsewhere because of space considerations (Demetriou & Spanoudis, submitted for publication). It is noted, however, that there seemed to be three major periods, with two phases in each. The production of a new kind of representation dominates in the first phase of each period (i.e., gross representational blocks, generic concepts, and general principles from 2 to 4, 6 to 8, and 11 to 13 years, respectively). The alignment and integration of representations in each period, (i.e., dual representations at 4–6, conceptual hierarchies at 8–11, and conditional reasoning at 13–16 years, respectively), dominate at the second phase. Thus, in period representations first proliferate and then they are integrated with each other generating new mental units opening the way for the next period. For example, 2–3-year olds can represent absolute magnitudes; 4–6-year olds can ally enumeration with object pointing to count objects. Integrating over these aligned actions, 6–8-year olds master a general number concept, which enables them, at the end of primary school, to master simple numerical analogies (e.g., 5:10 = 4:8) to inter-relate quantified dimensions of reality, such as weigh, size, distance, etc. Early in the next period, between 11 and 13 years, their principled understanding of number enables young adolescents to derive solutions by coordinating inter-definable representations (e.g., "Specify m given that $m = 3n + 1$ and $n = 4$"). In the later phase of this period completely abstract relations may be grasped, indicating that one set of representations may be used to explore and define another set (e.g., "Specify when is true that $A + B + C = A + Y + C$").

There seems to be a gross correspondence in the complexity of representations attained in the successive phases described above and the capacity of working memory as suggested by the three studies. In the 2–4 year phase, which was not examined here, a working memory capacity of one chunk would be enough to represent a representational block, which is characteristic of this phase. To align two representational blocks, which is possible in the 4–6 year phase, working memory of two chunks would be required. To refocus alignment from blocks to component representations within blocks, a minimum working memory capacity of 3 chunks would be needed, which is attained in the 7–11 year phase. Finally, at least four chunks, attained in early adolescence, would be needed to work out the relations between aligned units and reduce them to an overarching principle that can be aligned with other such principles.

6.2. Developmental inter-relations

At a first sight, panel A of Fig. 4 and the analysis above are consistent with the dominant view in developmental and differential psychology that the three systems are closely inter-related. All of the studies presented here suggested strongly that WM is the liaison between speed and *gf*. To further pinpoint these relations and differentiate between the developmental and differential roles of WM, we allocated all participants in three groups according to their performance on WM: low (from 0 to 1.99 units), medium (2 to 4.99 units) and high (5 to 7 units). Fig. 5 shows the development of g_f as a function of age and these three levels of working memory. It can be seen that high working memory individuals performed consistently higher than low working memory individuals throughout the age span studied here, although the effect was weak ($F_{2,\ 662} = 8.55$, $\eta^2 = .03$). However, the *gf* scores of young children with high working memory were much closer to the *gf* scores of their age mates than to those of older individuals with lower working memory. Interestingly, there was a limited difference between medium and high working memory individuals. It is very likely that this was due to the fact that the demand of the tasks used here varied between 2 and 4–5, which is exactly the capacity of the medium working memory individuals. Therefore, working memory higher than 5 units was not a big advantage for *gf* attainment, compared to WM in the range 2–5 units. In fact, when we ran the Model B above on these three groups of subjects, the WM–g_f relations were close to 0 in the low and the high WM group and .9 in the medium working memory group. Obviously, this pattern of relations reflects the finding of the structural models that the contribution of WM to the total effect of age on *gf* was a fraction that very rarely exceeded the one third of the total effect of age.

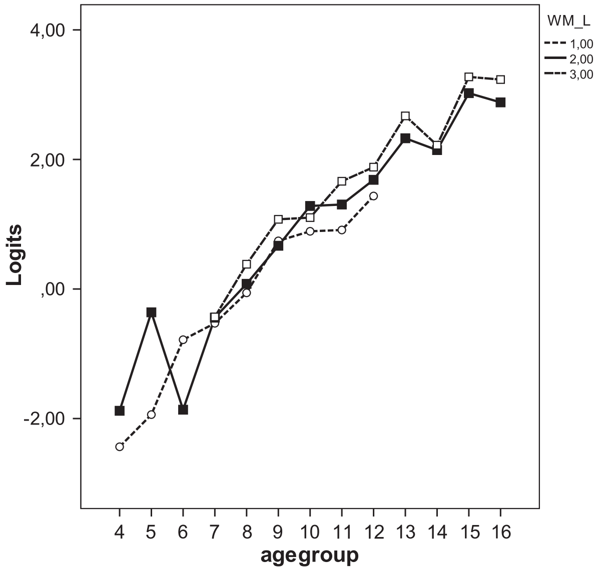


Fig. 5. Cognitive performance as a function of working memory level (i.e., low, 0–2; medium, 2–5; high, 5–7).

7. General discussion

The higher resolution of analysis allowed by our studies depicted a picture of intelligence and development that is considerably more refined than the picture depicted by extant theories, claiming that either speed (Coyle et al., 2011; Fry & Hale, 1996; Hale & Fry, 2000; Jensen, 1998, 2006; Kail, 1991) or working memory is a strong predictor of intellectual development and individual differences (Case, 1985; Halford et al., 1998; Kyllonen & Christal, 1990; Pascual-Leone, 1970). The present studies suggested that inconsistencies arise from seemingly paradoxical patterns of relations between processes that any overarching theory would have to accommodate. Below we will attempt to outline this theory.

7.1. Evolving cognitive structure and developmental cycles

Our findings about structure confirmed both the SLODRage prediction that cognitive processes differentiate from each other (prediction 4a) and the developmental prediction that they become increasingly coordinated with each other (prediction 4b). Differentiation was suggested by the fact that, with age, different types of mental processes are expressed through process-specific factors rather than through a more inclusive representational factor. These process specific factors tended to relate increasingly with a general factor at a subsequent phase, reflecting an integration of previously differentiated processes. This concurrent differentiation/integration of cognitive processes necessitates a redefinition of the nature of cognitive development. Our findings suggested that intellectual power increases with development because cognitive processes and reasoning evolve through several cycles of differentiation and integration where relations are dynamic and bidirectional. According to the present and other research (Demetriou, 2000; Demetriou & Kazi, 2001, 2006; Flavell, Green, & Flavell, 1995), differentiation goes from general cognitive functions to specific cognitive processes and mental operations. Integration follows the trend, focusing on increasingly specific processes and operations. Differentiation of cognitive processes allows their control because they may be individually regulated according to a goal-relevant plan. Integration of mental operations generates content-free inferential schemes that can be brought to bear on truth and validity. In both differential and developmental theories, the differentiation/integration process always applies on inferential processes. Moreover, in developmental theory, the state of their coordination frames the functioning of all other cognitive processes, such as language, mental imagery, and memory, imposing a stage-specific overall worldview (Piaget, 1970).

The pattern of relations between WM, reaction time to WM tasks, and *gf* in middle childhood is instructive. In early childhood, when WM and inference were not differentiated, reaction times to WM were related to WM performance but not to *gf*. This (negative) WMrt–*gf* relation was established in late childhood, when these processes were differentiated. This pattern suggests that children began to understand that too fast may impair memory performance but too slow may impair problem solving. Thus, they regulated their performance in each according to its own processing requirements.

Increasingly refined and focused differentiation/integration may be the background underlying the cycles of *gf* development. We remind that block-based inference cycles alternate with alignment phases in which blocks become units to be interrelated. Also, these cycles were concerted with cycles in speed–*gf* and WM–*gf* relations and change. At the beginning of *gf* cycles, at 6–8 and 11–13 years, which were marked by the creation of new mental units, the speed–*gf* relations rose and the WM–*gf* relations dropped. In these phases, change in all of these processes depended primarily on *G*. When alignment between mental units dominated, in the 4–7-, 9–11-, and 14–16-year phases, these relations were reversed: speed–*gf* relations dropped and the WM–*gf* relations rose. In these alignment periods, *G*-driven change in working memory and *gf* was stronger. Therefore, developmental cycles reflected variations in the relations between the various aspects of this mechanism. At the beginning of a cycle, when new concepts dominated, speed was a strong index of *G*, reflecting the spread of its influence over new cycle-specific representations, which could be supported by available WM capacity. Later in the cycle, when representations began to align, WM became a better index because representational alignment is WM-hungry by definition.

Therefore, we do assume that there is a general factor in operation which, like a conductor, is orchestrating the various developmental cycles. This *G* is a dynamic perpetually self-modifying system powered by three inter-dependent processes: (i) the "blessing of abstraction" (Tenenbaum, Kemp, Griffiths, & Goodman, 2011); (ii) alignment; and, (iii) the blessing of cognizance (Piaget, 1976). The first generates concepts based on a probabilistic inference mechanism that samples over statistical regularities in the environment. The second is a relational mechanism that binds representations together on the basis of relational similarities rather than object similarities. The third is "the act of becoming conscious" (Piaget, 1976, p. 332) and it allows self-monitoring, reflection, and metarepresentation. "Metarepresentation is the generative aspect of consciousness… [It] is an ideoplastic process that looks for, encodes, and typifies similarities between mental experiences (past or present) and between representations [generating] new mental operations, new higher-order rules integrating different operations, and new representations to stand for these new operations and rules" (Demetriou, Spanoudis, & Mouyi, 2011, p. 616). All three mechanisms are present since the first months of life (Dewar & Xu, 2010; Kopp, 2011; Tenenbaum et al., 2011; Zelazo, 2004). Concepts, inferential possibilities, and self-concepts at successive developmental levels are the visible products of this mechanism. Efficiency and smoothness of operation, WM capacity, and cognizance focus and precision are the underlying functional parameters that define its operation (e.g., Demetriou & Kazi, 2001, 2006). The concerting power of *G* comes from the dynamic inter-relations that it enforces between the various players involved (attention, WM, inference, etc.) rather than from the players sharing common components (van der Maas et al., 2006).

7.2. Representational complexity and management

WM development and *gf* development are alternative aspects of the state of mind at a given time (representational resolution and integrative precision, respectively) and change in both derives from the abstraction–alignment–cognizance mechanism (AACog) underlying the differentiation/integration cycles. Differentiation increases representational resolution causing representations to proliferate and AACog reduces ensuing mental load through pattern abstraction, alignment, and metarepresentation. Actually, deductive reasoning emerges from the statistically based pattern-deciphering mechanism (Demetriou et al., 2011; Ricco & Overton, 2011). This interpretation of development explicates three seemingly paradoxical and unrelated findings: (1) inductive reasoning is always more dependent on *G* than deductive reasoning; (2) the direction of effects between WM and *gf* can go either way; (3) although always commensurate in complexity, WM and *gf* only very weakly account for change in each other. Therefore, change in any one of them, *gf* in particular, may only come from development in their common causal agent: the AACog mechanism, which transforms inductive inference patterns into deductive reasoning schemes.

This is exactly what some recently completed intervention studies showed (Demetriou et al., submitted for publication). The first examined how learning to reason is related to speed, working memory, and *gf*. Instruction aimed to enable 8- and 11-year olds to reason analytically and command the fundamental arguments of deductive reasoning (i.e., modus ponens, modus tolens, and the fallacies). In sake of this aim children were instructed to understand the difference between truth and validity, grasp logical contradiction, necessity, and sufficiency, and differentiate between the logical arguments above. They were also instructed to generate mental models (Johnson-Laird, 2001) in order to evaluate alternative conclusions of an argument. In terms of the dual-process theory of reasoning (Evans, 2010; Ricco & Overton, 2011), this study aimed to enable children to move from automatic (System 1) to analytic (System 2) reasoning.

It was found that neither speed nor *gf* was related to change in reasoning performance and change in awareness about reasoning. Only working memory was an important predictor of learning in both. The higher it was the higher children ascended the scale of reasoning (from easy to difficult arguments) and self-awareness (from a gross to an analytic grasp of the processes involved). One might argue that the learning experience in this experiment condensed years of developmental time in a few weeks by forming and refining reasoning schemes and generating the metarepresentations needed to ponder and use them.

The second study focused on mathematical reasoning. Specifically, 9- and 11-year olds were instructed to transform verbal problems into the proper mathematical expressions, and solve mathematical analogies and simple algebraic reasoning problem. These problems varied in difficulty from simple (e.g., $a+2=x$, specify x if $a=10$) to more abstract and complex (e.g., specify when is true that $a+b+c=a+b+d$). Instruction aimed to raise awareness of mathematical relations, develop the skill to represent relations between actual entities in proper mathematical language, and use reasoning to specify mathematical relations. Interestingly, change in this study was related to *gf* and prior mathematical knowledge, but not to working memory or speed.

Therefore, the first study, which focused on the very mechanisms underlying *gf*, showed that working memory operated as a differential relay center for *gf* expansion. That is, the initial individual differences in working memory were analogically relayed into gains in reasoning and self-awareness schemes because of learning. However, the second study showed that this is not the whole story. Learning new concepts and processes germane to a domain of thought requires *gf* processes themselves and available domain-specific knowledge rather than representational capacity as such. This is so because domain-specific learning is a meaning making process where new information must be embedded into extant networks, these networks must be modified to accommodate the new information, and inferential processes must be naturalized, so to speak, into the specificities of the new domain. In psychometric terms, this kind of learning is a crystallization process where domain-specific knowledge and skills are more important than representational capacity. These findings are in line with two complementary lines of recent research.

On the one hand, there is research showing that the development from automatic to controlled reasoning depends on both the capacity of working memory and self-awareness of mental processes involved. Barrouillet and colleagues (Barrouillet, Gauffroy, & Lecas, 2008; Barrouillet, Grosset, & Lecas, 2000; Barouillet, Portrat, & Camos, 2011; Markovits & Barrouillet, 2002) showed that the development of deductive reasoning is a process of constructing mental models for real problems based on the content and knowledge available. The complexity of the models depends on working memory, because more capacity allows for more models and more pointers from them to information in long-term memory. Awareness of this process and ensuing executive control are important because they direct the final selection of models vis-a-vis the goal and their encoding into logical forms to be recalled later on (Barouillet, Portrat, & Camos, 2011). Along the same line, Fletcher and Carruthers (2012) argued that individual differences in the relative use of System 1 and System 2 reasoning come from individual differences in metareasoning, which is largely the result of cultural learning.

On the other hand, with development, learning is increasingly important for metareasoning because the increasing complexity of representations to be aligned multiplies the alignment options available. Therefore, integrating search and criteria for relevance into mental functioning would enhance cognitive efficiency because it would direct alignment and metarepresentation to the proper space of relevance that may be brought to bear on inference or concept construction (Wilson & Sperber, 2012). This makes meta-relevance, the systematic search for and evaluation of relevance, an important part of rationality, which was underestimated by both differential and developmental research so far (Stanovich, Toplak, & West, 2008).

7.3. Identifying the developmental and differential factors

Modeling suggested two major levels in mental organization, one for efficiency and one for representation. Relations between processes within levels were much stronger than across levels. At the one extreme, within each level, the speed-interference control and the storage-executive control relations, respectively, were almost collinear, technically scrapping each of these measures of control as a possible *gf* predictor. At the other extreme, age–speed–*gf* relations were high when WM was not taken into account. When it was included in the models, this relation faded away. This finding is consistent with recent neuroimaging evidence suggesting that control is confounded with other cognitive processes in brain activation as well (Meyers & Rohling, 2009).

These patterns suggest that relations between processes within the same level are of a different kind than relations between processes belonging to different levels. Specifically, processes in the same level are *structurally entangled* for two reasons. First, they share common components. In the efficiency level, attention focusing (Stankov & Roberts, 1997) and stimulus discrimination (Demetriou et al., 2008) are part of every speeded performance task, regardless of their complexity. In the representational level, WM and *gf* share common storage (Colom et al., 2008) and management processes (Baddeley, 2012). Second, the response mode is a factor of structural entanglement within each level (e.g., reaction times vs. mental operations), because it channelizes the output to activate channel-specific elements. Relations across levels are constructed relations. Therefore, processes across levels are *developmentally entangled*. That is, change in a process in one level, such as speed, is functionally necessary for change in a process in the other level, such as WM or *gf*. However, it is not sufficient because the required processes need to be assembled as such.

Therefore, any process may be a differential or a developmental factor relative to another process, depending on the level they belong to. Within levels, all processes are differential factors relative to each other, because the state of any one conveys accurate information about the state of the rest regardless of age. However, any process may be a developmental predictor of another process, if they belong to different levels, because the state of the first foretells what age-related experiences, such as learning or personal construction, might do to the second. These experiences operate as translational factors which may transform the possibilities indicated by the predictor into actualities in the other process. Under these conditions, age is a generic index of translational factors. One might object here that speed was a moderately but stably good predictor of WM (their relation was always around −.5), despite the fact that they belong to different functional levels. This is because WM bears properties of both levels. On the one hand, WM is a time-constrained process like all speeded performance tasks. On the other hand, it involves mentation like all representational tasks. Thus, it is a liaison between the two functional levels. It is reminded that the predictive strength of a process, differential or developmental, varies with developmental cycle.

It is notable that the cycles of intellectual development captured here are reminiscent of similar cycles in brain development. At the level of overall brain functioning, there seem to be significant brain growth spurts at the age of 2–4, 6–8, 10–12 and 14–16 years, tractable in changes in the amount of EEG energy found in the alpha-frequencies (Epstein, 1980, 1986). These functional changes may be related to cycles of changes in brain architecture. Thatcher (1992) claimed that changes within stages of cognitive development (inter-linking and alignment here) are associated with improvements in neuronal networking within brain regions whereas transitions across stages (generation of new mental units) are associated with improvements in networking between brain regions. Shaw et al. (2006) showed that there are cycles of changes in cortical thickness, because thickening in early childhood and in early adolescence are followed by phases of thinning (or pruning), both of them more pronounced in more intelligent individuals. Moreover, different aspects of the brain, such as white matter volume and microstructure and cortical thickness (Tamnes et al., 2011), and different brain regions, such as prefrontal, parietal, and thalamic regions (Luna et al., 2001), change in different rates with age. It would be a big step forward to map the cycles of changes in the various cognitive processes studied here on the cycles of brain changes. This might show, on the one hand, how changes in one level of functioning are transformed into possibilities for the next level, what is specific to each next level, and how this may feedback on the lower level. For instance, how cortical proliferation relates to new representational alignment possibilities? How subsequent cortical thinning relates to the transcription (metarepresentation) of an aligned network into a new mental unit? How co-activation of storage, inhibition, and sequencing networks generate cognizance?

Obviously, the present findings need to be verified and refined by life-span studies especially designed to highlight the patterns and relations observed here. Admittedly, the variation between studies in tasks, procedures, and sample size, that is unavoidable when the various studies are separated by many years, may interfere with developmental and individual difference patterns and relations, probably confounding age changes with task- or sample-specific differences. These new studies would be a big step forward anyway, because they would further expand our understanding of developing mind, even if they would modify the picture drawn here. Moreover, they may bring developmental, experimental, and the differential approaches to intelligence closer to each other and to the allied fields, such as brain research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.intell.2012.10.010.

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