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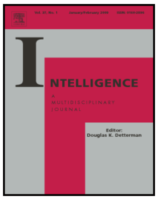

Relations between speed, working memory, and intelligence from preschool to adulthood: Structural equation modeling of 14 studies

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ABSTRACT

We posit that fluid intelligence (Gf) develops in four cycles, with two phases in each cycle, each distinctly connected with changes in processing speed and working memory. New representational units emerge in the first phase of each cycle at 2–4 (representations), 6–8 (inference based concepts), and 11–13 years (principles) and they are integrated into wider systems in the second phase, at 4–6, 8–11 and 13–16 years. We hypothesized that cycle transitions are better predicted by speed and phase transitions by working memory. To test this hypothesis several published studies were selected which measured speed, WM, and Gf at one or more of the age phases concerned. In structural equation models applied on each phase speed was regressed on age, working memory was regressed on age and speed, and Gf was regressed on all three. In line with the hypothesis, in the first phase of each cycle the speed–Gf relations were high and WM–Gf relations were low; this pattern was inverted in the second phase. The role of executive processes strengthened in the second phase of all cycles. The implications for developmental and differential theories of intelligence are discussed.

There is general agreement that human intelligence involves information integration processes activated when dealing with new information or problems. Inference, inductive or deductive, rule bound or heuristic, is a major part of these processes. It underlies psychometric fluid intelligence (Gf) (Carroll, 1993; Jensen, 1998; Spearman, 1927) and problem solving and reasoning studied by developmental (Case, 1985; Halford, Wilson, & Phillips, 1998; Piaget, 1970) and cognitive researchers (e.g., Johnson-Laird, 2013; Rips, 2001). Information processing theories of human intelligence maintain that individual or developmental differences in Gf reflect differences in processing speed (Jensen, 1998) or working memory (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990).

However, the exact role of speed and working memory is still debated. Some researchers emphasize speed as a purer index of the quality of information processing in the brain (e.g., Jensen, 1998). This interpretation is based on studies which estimate the relation between speed and intelligence

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without involving working memory. Others emphasize working memory because it is the workspace of thinking (Kyllonen & Christal, 1990). Studies emphasizing working memory usually measure all three constructs in young adults, when working memory is the dominant predictor of Gf, according to the patterns to be described below. Finally, others assume a causal linear relation between them such that changes in speed cause changes (or differences) in working memory which, in turn, cause changes (or differences) in Gf (Case, 1985; Coyle, Pillow, Snyder, & Kochunov, 2011; Kail, 1991; Kail & Ferrer, 2007). However, this chain of relations may only reflect the fact that working memory tasks are both timed, like speed tasks, and require information management, like Gf tasks, rather than a causal sequence. In fact, there is evidence that control of attention is common to all, speed, WM, and Gf, explaining their relations (Cowan, Morey, Chen, & Bunting, 2007; Engle et al., 1999; Stankov & Roberts, 1997).

Table 1
Summary of the studies selected for modeling in reference to selection criteria.

Study/data type	Age group/phase	N	Speeded performance/inhibition	Working memory	Cognition
Miller & Vernon (1996) Correlations/SD	4–6	109	Visual matching (speed)	Recall of color or shape sets presented sequentially or simultaneously	Gf: Object assembly, picture completion, block design
Podjarny et al. (2013) Correlations/SD	4–6	66	2 day/night Stroop-like and a dragon inhibition tasks (inhibition/control)	Forward digit span, backward digit span, counting and labeling	Raven-like matrix task, DCCS, Flexible item selection
Astle et al. (2013) Correlations/SD	4–5	69		Counting and labeling, corsi	DCCS, using maps to locate an object in a room (dual representation)
Bernstein et al. (2007) Raw data	3.5–5.5	72	day/night Stroop-like task (inhibition)	Counting and labeling, BDS	DCCS, theory of mind, false belief
van der Ven et al. (2012) Raw data	Four waves at 6.5, 7.1, 7.5 and 8.1 years	211	Three congruent (speed) and three incongruent (inhibition/control) Stroop-like animal and figure recognition, and Simon task	Backward digit span (BDS), odd-man out, keep-track	DCCS, category shifting guided by color prompt, trail making
Joined Kail (2007), and Fry & Hale (1996) Raw data	6–7 8–10 11–13 14–adult	91 216 119 109	Visual matching Cross out	Reading span Listening span	Raven test
Swanson & Kim (2007) Correlations/SD	Two waves tested at 7 and 8 years	353	Digit naming, letter naming (speed)	STS: FDS, word span, pseudoword span, updating. WM: Listening Sentence Span, Semantic Association Span, Digit/Sentence Span, BDS, Corsi-like, mapping directions task	Semantic based word problems, WISC mental calculation word problems, retrieved processing components of word problems, computational fluency
Berg (2008) Correlations/SD	8–12	95	As above	As above	As above
Brydges et al. (2012) Correlations/SD	7 9	215 95	Visual discrimination (speed) incongruent Stroop, and RT to go/no-go tasks (inhibition/control)	BDS, Letter–number sequencing, sentence repetition	Gf: Cattell culture fair test (i.e., series completion, matrices, odd-one out, topology), WISC block design Gc: WISC picture naming, word definitions, information. Fluency: WCST, verbal fluency, letter monitoring
Nettlebeck & Burns (2010) Raw data	8–10 11–13 14–30 31–80	118 84 105 169	WISC digit symbol, Woodcock visual matching, inspection time, simple RT, Odd-man out (speed)	Mental swaps Picture recognition WISC FDS	Cattell culture fair test
Demetriou et al. (2005) Raw data	8–10 12–14	60 60	Three congruent (speed) and three incongruent (inhibition/control) Stroop-like verbal, numerical, and figural tasks	Word FDS, Digit FDS, Visuo/spatial WM, simple listening WM span	Inductive and deductive verbal, spatial, and mathematical reasoning,
Leonard et al. (2007) Correlations/SD	14	204	Simple visual identification, perceptual discrimination (speed), visual identification under mental rotation (control)	Pseudoword FDS, Woodcock auditory working memory, simple listening WM span task	Gf: WISC block design, picture completion tests. Language: Vocabulary, discourse understanding
Rijsdijk et al. (1998) Correlations/SD	16	213	Letter, digit recognition (speed), and choice RT (control)	WISC digit span, coding	Gf: Picture completion, picture arrangement, block design, object assembly. Gc: Information, comprehension, arithmetic

Demetriou et al. (2013) showed recently that the relations between these constructs are more complicated than originally assumed, because they vary with growth. Specifically, speed increases and WM expands. Gf evolves along a reconceptualization sequence (ReConceP) where changes in the nature of representations alternate with changes in the command and interlinking of representations constructed earlier. This sequence involves four reconceptualization cycles with transitions from action-based episodic representations to symbol-based mental representations at 2 years (Re), from mental representations to inference-based concepts at 6 years (Conce) and from concepts to logically-based principles (P) at 11 years. Transitions within cycles occur at 4 years, 8 years, and 14 years, when relations between the representational units constructed earlier are worked out—obviously age boundaries are approximate. They found that changes in Gf were predicted by speed at the first phase of each ReConceP cycle (i.e., at 6–8 years and 11–13 years) and by working memory at the second phase (i.e., 4–6 years, 8–10 years, and 13–16 years). They suggested that this pattern reflects differences in the processing requirements of developmental acquisitions.

The reader may have noticed that the timing of the four cycles is reminiscent of other cognitive developmental theories, such as Piaget's (1970) and the neo-Piagetian theories (e.g., Case, 1985; Fischer, 1980; Halford et al., 1998; Pascual-Leone, 1970). It is noted that, on the one hand, the convergence of theories in concern to the timing of intellectual changes suggests an important empirical phenomenon needing explication. This is one of the major aims of the present study. It is also noted, on the other hand, that our interpretive framework focuses on the information processing and representational characteristics of the successive developmental cycles rather than their logical (Piaget) or schematic characteristics discussed by other theories. This will be elaborated later on in the discussion.

This article aims to explore the validity of these alternating speed–Gf and WM–Gf relations by using several independently published studies. To qualify for inclusion, a study ought to satisfy three requirements. First, it would have to include measures addressing speed of processing, short-term and/or working memory, and Gf. In regard to speed, all studies involved Simon-like, Stroop-like (Stroop, 1935), inspection time, and stimulus naming speed performance measures. In concern to working memory, all studies involved tasks measuring both storage and executive processes. There was more variation in the tasks addressed to Gf. Many of the studies involving younger children used primarily tasks inspired by developmental theories, such as reasoning, mental flexibility, and executive control tasks. The studies involving older children, adolescents, and adults used reasoning tasks addressed to inductive and deductive reasoning and standardized intelligence tests such as the Wechsler Intelligence Scale for Children (WISC), the Raven test or cognitive ability tests. According to psychometric theory, variation between tasks in the cognitive processes they activate is not a major measurement problem because of the "indifference of the indicator" principle (Spearman, 1927). That is, all tasks correlate with *g* and thus they all reflect the state of *g*, regardless of their particular characteristics (Jensen, 1998).

Second, the studies would have to include one or more of the following age phases: 4–6 years, 6–8 years, 8–10 years, 10–13 years, and 13–16 years or older.

Third, sample size must be sufficiently large to allow structural equation modeling. A rule of thumb was to have a minimum total of about 100 participants in a study. In fact, in many of the studies this criterion was amply satisfied, even within age groups.

However, an exception was allowed for three developmental studies (Astle, Kamawar, Vendetti, & Podjarny, 2013;

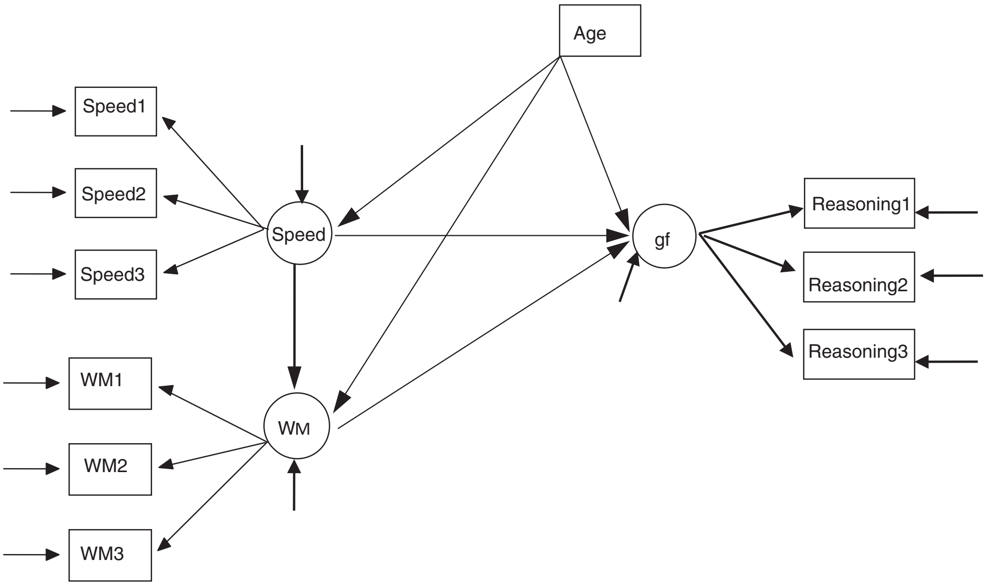

Fig. 1. The general model for testing the structural relations between age, speed, working memory, and Gf. Note: The statistics and structural relations of the models fitted onto the various studies are presented in Table 2.

Table 2
Effects of speed and working memory on Gf as a function of age.

			WM	Gf regressed on		Age effect on Gf	Fit indexes				
Study	Age	N	Speed	Speed	WM	Indirect	χ^2	DF	P	CF1	RMSEA
Miller & Vernon — Gf	4–6	109	−.19	−.18	.77	.60	41.70	29	.06	.97	.06
Van der Ven et al.	6.5	211	.39	−.29	.60	.01	904.13	673	.00	.91	.04
	7.1		.35	−.20	.32	.01					
	7.5		.26	–	.92	.01					
	8.1		.54	−.12	.71	.01					
				−.33	.88	.01					
Swanson & Kim	6–8		.88	.77	.30	.55	404.52	105	.00	.92	.09
	7–9		.69	.28	.78	.52					
Berg	8–11	90	−.35	.30	.65	.50	21.76	20	.08	.99	.03
Joined Kail	6–7	91	.10	.91	.31	.58	61.60	30	.01	1.00	.08
and	8–10	216	.58	−.06	.64	.23					
Fry & Hale	11–13	119	.59	.83	.26	.26					
	14–20	109	.36	.15	.91	.14					
Nettelbeck & Burns	8–10	118	1.00	–	.71	.27	417.56	265	.00	.92	.07
	11–13	84	1.00	.84	–	.44					
	14–30	105	.84	.51	.74	.25					
	31–80	169	.89	.86	.47	−.70					
Demetriou et al.	8–10	60	−.37	−.20	.39	.05	73.20	68	.12	.99	.04
	14–16	60	−.43	−.26	.62	.45					
Leonard et al	14	204	.46	.21	.75	.11	86.76	59	.01	.97	.05
Rijsdijk et al.	16	213	−.42	−.10	.62	–	42.09	38	.30	.99	.02

Bernstein, Atance, Metzoff, & Loftus, 2007; Podjarny, Kamawar, Vendetti, & Astle, 2013; see Table 1) which were considered crucial for highlighting the relations between the constructs of interest in the 4–6 years phase. These three studies did not use speeded performance tasks. However, they examined inhibition, which was examined by speeded performance tasks in many of the other studies selected. It will be demonstrated below that distinguishing the role of inhibition from the role of the other processes of interest emerged as a pivotal issue. Also, these studies examined fewer children (circa 70) than the criterion. On the one hand, this is common in developmental research involving preschool children. On the other hand, the limited sample size of each study may be compensated if all three of them are included in a multiple group analysis where statistical power is estimated in reference to the sum total of participants across studies rather than in each of them separately (Bentler, 2006).

Obviously, there are differences between studies in the specific measures addressed to the three constructs of interest. Also, the grouping of age years was not always perfect. This is understandable because the various studies selected were independently conceived and executed. However, variation across studies in the precise nature of the measures used to address the three types of processes may provide an advantage for the present purposes, because it can show if the patterns predicted are born out despite this variation. In fact, including different studies in multiple group analysis where equality constraints may be imposed across studies for measures supposedly examining the same construct provides a strong test for their comparability.

The same model was tested on all studies (see Fig. 1). Specifically, speed was regressed on age, working memory was regressed on age and speed, and Gf was regressed on age, speed, and working memory. Non-significant and very low relations (below .1) were dropped and the model was re-tested. Only values from final models are reported.

1. Studies and results

To facilitate presentation, we present the various studies according to the age phases covered, following the succession of cycles and phases as outlined in the introduction. The age phase covered and the tasks used by each study are summarized below and in Table 1. We refer the interested reader to the original publications for more information. Fit indices and structural relations between constructs in each study are shown in Table 2. To facilitate inspection of the main trends found, Fig. 2 shows the mean structural relations

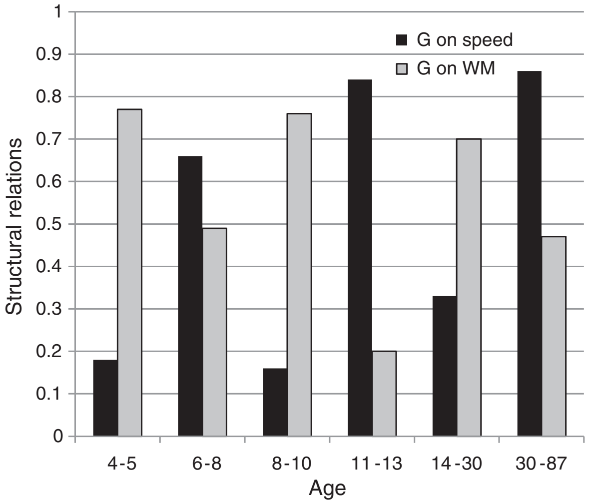

Fig. 2. Structural relations between speed–Gf and WM–Gf as a function of age. Note: The minus sign was omitted from the speed–Gf and the WM–Gf relations to facilitate comparison. Note 2: The studies which did not include measures directly standing for speed (i.e. Astle et al., Brydges et al., Bernstein et al., and Podjarny et al) were not included in the estimation of the means shown here.

between speed and Gf and WM and Gf as a function of developmental phase.

1.1. From representational alignment to concepts

Miller and Vernon (1996). This study focused on the relations between speed, working memory, and intelligence from 4 to 6 years of age. It included 109 children about equally drawn among 4-, 5-, and 6-year old children ($M_{age} = 5.5$, $SD = .85$ years).

Eight tasks addressed speed. There were four simple tasks where children judged if two stimuli were the "same" or "different" (in shape, color, size, or number—always between 1 and 3 squares compared with 1-3 triangles). There were three more complex tasks where children judged if "target" stimulus (shape or color, presented for 1000 ms) was present in a string of stimuli presented (for 250 ms) after the target presentation. There was also a task where children chose the side of the screen where an arrow appeared (left or right).

Five tasks addressed working memory. Four tasks required children remembering color or shape sequences (from 2 to 7) presented either sequentially or simultaneously. There was a fifth task addressed to acoustic span which required children remembering sequences of tones differing in pitch.

To address intelligence the Wechsler Preschool and Primary Scale of Intelligence-Revised (WPPSI-R) was used. Fluid intelligence was addressed by object assembly, picture completion, mazes, geometric design, and block design. Crystallized intelligence was addressed by information, vocabulary, arithmetic, similarities, and comprehension tests.

Because of the relatively limited sample size (109 participants) we tested the model on several combinations of nine of the 23 measures described above, three for each of the main constructs (i.e., speed, WM, and either Gf or Gc). Here we present only one of these models, that which involved Gf for intelligence. This model included three of the complex tasks addressed to speed (judge if two numbers are the same and find if a target stimulus is present in a sequence). For working memory, we selected one color, one shape sequence, and the acoustic task. Finally, object assembly, block design, and picture completion we selected to represent Gf ($\chi^2 = 41.70$, df = 29, p = .06, CFI = .97, RMSEA, .06). The fit of this model was good. Specifically, in line with our prediction for this age phase, the speed–Gf relation (−.18) was low and non-significant but the WM–Gf relation was high and significant (.77). The direct age–Gf effect was also low and non-significant, as expected (.16), although the indirect effect was high (.60). It is noted that when the speed factor was indexed by the three simple rather than the complex tasks, neither the speed–Gf relation (−.27) nor the WM–Gf relation (.80) were basically affected. Therefore, the pattern of relations between speed and WM, on the one hand, and Gf, on the other hand, came as expected for this age phase.

1.1.1. Mapping the core of representational alignment

Developmental researchers emphasize the role of three distinct but interrelated processes in early intellectual development: Executive control, dual representation, and theory of mind (ToM). Thus, specifying the place of these processes in the network of relations studied here may highlight how intellectual ability is formed at this early phase. To meet this aim, three studies were selected. All three examined inhibition and working memory but each of them focused on one of these target processes. Thus, as a set, these three studies can highlight how basic information processing capacities are invested in some fundamental dimensions of intelligence.

Podjarny et al. (2013). This study included 66 children (29 boys) from 4–6 years of age ($M_{age} = 58.91$ months; $SD = 7.06$; range = 43–72 months). In this study, two Stroop-like tasks were used to address inhibitory control. In a variant of the Day/Night Stroop task, children were presented with black cards and white cards, and were asked to respond "white" to the black cards and "black" to the white cards. A second task measured motor inhibitory control. In this task children saw two puppets, a nice and a naughty dragon and they were instructed to follow the nice dragon's instructions, but not to follow the naughty dragon's instructions (e.g., "touch your nose").

Three tasks addressed working memory: Forward and backward digit span and counting and labeling. The last is a dual-process working memory measure requiring to organize information in two chains, one for counting and one for naming objects and recall accordingly. In a sense, this task tests how alignment can take place in working memory.

Finally, three tasks addressed Gf. These were a Raven-like matrix completion task, Zelazo's dimensional change card sort, and a flexible item selection task.

A simplex model was found to have an excellent fit to the data ($\chi^2 = 19.24$, df = 25, $p = .79$, CFI = 1.00, RMSEA = .00). In this model, performance on working memory was fully accounted for by inhibitory control (1.00) and performance on the Gf tasks was very highly accounted for by working memory (.84). The indirect effect of inhibitory control on Gf was high (.84) but the effect of age was not significant (.22). In fact, dropping WM and using inhibitory control as the predictor of Gf yields the same high relation (.93) and it does not significantly affect the model fit ($\chi2 = 19.07$, df = 25, p = .79, CFI = 1.00, RMSEA = .00).

Astle et al. (2013). This study involved 69 4–5-year-old children ($M_{age} = 53.5$; $SD = 4.0$; range = 47–61 months). The Dimensional change card sorting task was used to examine inhibition. The counting and labeling task and the Corsi task were used to examine working memory. To examine understanding of representations, children were asked, following DeLoache (2000), to use maps representing two model rooms to find objects hidden in them. There were two tasks, differing in the arbitrariness of information presented on the maps. Two models were found to have an excellent fit to the data. In the first, which was close to the prototype model shown in Fig. 1, inhibition was regressed on age (.34), WM was regressed on inhibition (1.00), and representation ability was regressed on WM (.95) ($\chi^2 = 8.57$, df = 7, p = .28, CFI = .97, RMSEA = .06, model AIC = −5.43). In the second run, inhibition was regressed on age (.34), and both WM (.94) and representation ability were regressed on inhibition (.98), ($\chi^2 = 8.44$, df = 7, p = .30, CFI = .98, RMSEA = .06, model AIC = −5.56). Thus, the second model is slightly better.

Bernstein et al. (2007). This study (Experiment 2) tested 72 children equally drawn among 3.5 to 5.5 years of age ($M_{age} = 54.4$; *SD* = 1.5; range = 42–66 months). Of the various tasks used in this study, only six were chosen here. Two tasks examined inhibition (the Dimensional Change Card Sort and the Day/Night task as above), two examined working memory (the Count and Label and the Backward Digit Span task) and two sets of tasks examined theory of mind (ToM) and false belief. These later tasks examined if children could differentiate between their own and another person's representations according to each one's access to information. Two models were again found to fit the data very well. In these models a factor was created for each of these three pairs, standing for inhibition, WM, and ToM, respectively. In the first model, inhibition was regressed on age (.83), WM was regressed on inhibition (.90) and ToM was regressed on WM (.67), ($\chi^2 = 12.82$, df = 12, p = .38, CFI = 1.00, RMSEA = .03, model AIC = −11.18). In the second model, inhibition was regressed on age (.81) and both WM (.98) and ToM (.65) were regressed on inhibition, ($\chi^2 = 13.99$, df = 12, p = .30, CFI = .99, RMSEA = .06, model AIC = −10.01). Technically, the first model fits the data better than the second, although they are barely discriminable from each other.

All three studies suggested that in the 4–6 years phase inhibition and working memory are almost completely interchangeable as predictors of higher level cognition (Gf in Podjarny et al, dual representation in Astle et al., and ToM in Bernstein et al). One might object that the various processes may not be comparable across studies because of variations in the measurements used. In response to this objection, the three studies above were pulled together into a common three-group model where the most similar measures were retained from each study to stand for inhibition and working memory. Specifically, the card sorting and the day/night tasks were used from Podjarny et al. and from Bernstein et al., and the card sorting from Astle et al were used to index inhibition. The counting labels and backward digit span from Podjarny et al and Berstein et al and counting labels and corsi from Astle et al were used to index working memory. The Raven-like and flexible item selection were retained from Podjarny to stand for Gf; ToM and false belief were retained from Berstein et al. to stand for ToM; the two dual representation tasks were retained from Astle et al. The measurement–factor relations for inhibition and working memory were constrained to be equal across the three groups. No equality constraint was imposed for the three cognition factors, because they were supposedly different (Gf, ToM, dual representation). To test the assumption suggested above about the pivotal role of inhibition, both working memory and cognition were regressed on inhibition in all three studies. To test the assumption that the role of inhibition is the same for all three cognitive processes, the inhibition-working memory and the inhibition–cognition relations were constrained to be equal across the three groups. The fit of this model was very good ($\chi^2 = 62.41$, df = 42, p = .02, CFI = 1.00, RMSEA = .08, model AIC = −21.59). All relations were significant and high and practically identical with the relations uncovered by each of the three separate models.

Therefore, it seems that the mental core here is the ability to articulate a mental plan allowing the alignment of representations with each other and actions. When present, it can be used to relay information in working memory and call upon it as required (e.g., forward or backward) or search for and decode relations between stimuli or implement rules for specific problem solving. In other words, this core executive plan is a general purpose program that may be transcribed into more specific programs according to representational and problem solving needs (e.g., store and recall information, inference, and problem solving in different domains).

1.2. Establishing concepts

van der Ven, Kroesbergen, and Leseman (2012, 2013). This is a longitudinal study that included 211 children (107 boys) who were 6 years old at the first testing ($M_{age} = 73.60$ months; *SD* = 4.51; range = 58–87 months). Testing took place in four waves with 6-month intervals: in fall (W1, 6.5 years) and spring (W2, 7.1 years) of first grade and fall (W3, 7.5 years) and spring (W4, 8.1 years) of second grade. Therefore, this study presents an interesting test of the shift of relations from the first to the second phase of the 6–10 years cycle. This is so because children were first examined at the beginning of the first phase of this cycle and they were followed until the second phase. According to the model put forward here, there should be a weakening of the Gf–speed relation and a strengthening of the Gf–WM relation across testing waves.

Speed was measured by three sets of tasks: (1) a Stroop-like task requiring recognition of an animal with congruent (e.g., cow, sheep, duck, or pig) or incongruent head (e.g., a sheep with cow head); (2) a Stroop-like task requiring recognition of congruent geometrical figures (a large circle made of small circles) or incongruent figures (e.g., the small component circle making a triangle); and (3) a Simon task where children had to locate an animal appearing either in the center (control condition) or in the left or right side of the screen. Working memory was addressed by three tasks: the backward digit span (score from 0 to 12, span from 2 to 4 digits); the odd-one out task, which requires to recall, in presentation order, the locations of figures differing from two other figures (score from 3 to 16, span from 1 to 4 items); and a keep track task where children had to recall the last object of several categories (e.g., sky (sun, moon, stars, cloud), fruit (strawberry, pear, cherry, banana), shapes (square, triangle, circle, heart), animals (dog, cat, fish, bird)) presented in succession (score from 1 to 20, span from 1 to 4 items).

Three tasks were selected to examine executive control. The animal shifting task required naming one of two stimuli belonging to one of two categories (e.g. fruit or animal) depending upon the color of the screen (yellow or purple). The trail making test required connecting number-marked circles from 1 to 10, alternating between two sets both numbered from 1–10 but differing in color (blue or orange). The sorting task required alternating between two sorting rules, according to color and according to shape. It is noted that these tasks activate processes required by traditional Gf tasks, such as consideration of alternatives and matching properties following a rule. For instance, Raven-like or classification tasks do require these processes. Children were also given a standardized mathematics test examining command of the number line, arithmetic operations, measuring, and mathematics applications. This test was given at the four testing waves, about three months later than the tests above. Children were given the Raven's Standard Progressive Matrices at the last wave.

Implementing the model on this study was rather complicated. There was a factor for each of the three constructs at each of the four testing waves indexed by the three respective measures. That is, three speeded measures for processing speed, the three working memory measures for working memory, and animal shifting, trail making, and sorting for Gf. At the last testing there was a second Gf factor (Gf_2) indexed by performance on the Raven test and the mathematics test addressed at this wave. Speed was regressed on age only at the first wave, because the relation was very low due to very limited age variation. Working memory was regressed on speed and Gf was regressed on both speed and WM of the same wave at all four waves with two exceptions: WM at the third wave was also regressed on WM of the second wave. Gf_2 at the fourth wave was regressed on speed, WM and $Gf_{1.}$ Residual errors of the same measure across waves were allowed to correlate, to purify the factors within waves from any possible task-specific systematic variation caused by repeated testing.

The model was tested in two runs. In the first run, speed was represented by reaction times to the congruent conditions. In the second run speed was represented by the incongruent conditions. The fit of the second model was slightly better (Model AIC = −440.76 and RMSEA = .040 as contrasted to −427.54 and .041, respectively) and acceptable, given its complexity, ($\chi^2 = 904.13$, df = 673, $p = .01$, CFI = .91, RMSEA = .04). The relations in this model were close to expectations. The speed–Gf relation was significant only at the first two waves: −.29, −.23, .09 and −.11 at 6.5, 7.1, 7.5, and 8.1 years, respectively. The WM–Gf relation dropped drastically from .60 at 6.5 years to .32 at 7.1 years and then increased again to .92 at 7.5 years and .71 at 8.1 years. The speed–WM relation was always significant. Notably, $Gf_{2,}$ standing for performance on the Raven and the mathematics test, was significantly related to both speed (−.33) and Gf_1 (.22) but WM was its dominant predictor (.89). It is noted that this model differed from the model including the congruent rather than the incongruent conditions only in the speed–Gf relations. Specifically, when the congruent relations were involved these relations never reached significance (i.e., −.20, −.20, .11, −.04, at the four waves, respectively, and −.22 for the speed–Gf_2).

Overall, the trends came as expected. Admittedly, the speed–Gf relations should have been higher at the first two waves. It may be the case, however, that the mental flexibility tasks representing Gf here are closer to WM in this study. That is, the mental shifting requirements of these tasks require goal representation and binding with response options that are more similar to WM tasks than in standard problem solving and reasoning tasks indexing Gf. Also, the higher speed–Gf relations under the incongruent conditions suggest, in line with the studies analyzed above, that command of attentional control is a major aspect of the transition into the conceptual cycle. When already in the second phase of this cycle, WM completely dominated as a predictor of the more conventional Gf_2 factor, in line with expectations and the studies to be presented below.

Swanson and Kim (2007). This is a two-wave longitudinal study that involved 353 children (186 boys and 167 girls) drawn from first through third grade of primary school at first testing (M_{age} 92.62 months, $SD = 11.67$ months) and retested one year later (320 children, 154 boys and 166 girls).

Speed of processing was measured by two tasks, digit and letter naming speed. Children were asked to name two arrays (36 in each array) of number digits and letters as fast as possible.

Short-term storage was tested by four tasks: forward digit span (from WISC-III), word span (one- or two-syllable high frequency words), pseudoword span (strings of nonsense one syllable words), and updating (recall the last three digits of sets of 3, 5, 7, and 9 digits). Working memory tasks required holding increasingly complex information in memory while responding to a question about the task. The questions served as distracters to item recall because they reflected the recognition of targeted and closely related non-targeted terms. They were four phonological tasks (the Listening Sentence Span required recalling the last word of sets of sentences; the Semantic Association Span required the children recalling the category words for sets of category-member words, the Digit/Sentence Span required the children remembering number digits embedded in sentences, and Backward Digit Span from WISC-III) and two visual–spatial tasks, the visual matrix task (assessing the ability to remember visual sequences within a matrix) and the mapping directions task (assessing the ability to remember a sequence of directions on a map).

Executive function was addressed by several fluency measures. The categorical fluency task required children naming as many animals as possible in 60 seconds; the letter fluency task required them generating as many words as possible beginning with letter B in 60 seconds. The random generation of letters and number tasks asked them first to generate as quickly as possible numbers (or letters) in sequential order and then to quickly write numbers (or letters) in a random nonsystematic order.

Gf was addressed by several problem solving tasks related to mathematics and language ability drawn from the Test of Word Reading Efficiency, Wechsler Individual Achievement Test, WISC-III, Wide Range Achievement Test, Third Edition (WRAT-III) and Woodcock Reading Mastery Test. Specifically, children solved (i) word problems assessing calculation as a function of variations in their semantic structure, (ii) the mental calculation word problems from WISC-III, (iii) retrieved processing components of word problems (e.g., "Fifteen dolls are for sale; seven dolls have hats; the dolls are cute. How many dolls don't have hats?"), (iv) arithmetic computation problems involving the four arithmetic operations, and (v) computational fluency problems requiring to write in 2 minutes as many answers as possible to 25 facts and algorithms. Reading skill, phonological deletion, and reading comprehension addressed language ability.

This study included two testing waves. Thus, the factor-measurement relations were constrained to be equal across the two testing waves. The relations between factors were allowed to vary freely. This manipulation implemented the assumption that the latent constructs are similarly identifiable at the two testing waves but their relations may vary. Under these constraints, the fit of the model was acceptable ($\chi^2 = 404.52$, df = 105, p = .00, CFI = .92, RMSEA = .09, SRMR = .06). According to our prediction, the speed–Gf relation would be high and the WM–Gf relation would be low at the first wave. At the second wave, the speed–Gf relation would decrease and the WM–Gf relation would increase. This is precisely what was found. Specifically, at the first testing wave the speed–Gf relation was very high (.74) but the WM–Gf relation was much lower (.30), although significant. The age effect was high at this phase (.55). At the second wave, the relative magnitude of these relations was inverted (.28 and .77, respectively), although they were both significant. The age effect dropped slightly (.52). It is noted that when fluency was not included in the model, the speed–WM relation was high at both waves (.88 and .69, respectively). When included, it completely dominated as predictor of WM (it was 1.00 at both waves). Interestingly, in this later case, fluency exerted a significant but moderate indirect effect on Gf (.30) at the first wave, which increased drastically at the second wave (.77).

Berg (2008). This study is complementary to the Swanson and Kim (2007) study above because it addressed the same tasks to 8–12 year-old-children. Specifically, this study included 90 children (44 boys and 46 girls) from Grades 3 through 6 ($M_{age} = 121.90$; $SD = 12.44$; range = 98–145 months).

Speed of processing was measured by two tasks, digit naming (as above) and digit articulation (repeat a pair of single-syllable digits as quickly as possible five times, e.g., 1–4, 5–8, 3–6, and 2–9).

Short-term storage space (STSS) was assessed by forward digit and forward word span. Verbal working memory was assessed by semantic categorization, auditory digit sequencing. Visual working memory was assessed by visual matrix task and the Corsi block task. All but the Corsi task were taken from Swanson and they are as described above.

The WRAT-III was used to assess arithmetic and reading achievement as in Swanson.

Berg's study addressed most of Swanson's tasks to 8–12 year olds. The fit of the model was excellent, ($\chi^2 = 21.76$, df = 20, p = .08, CFI = .99, RMSEA = .03). In line with expectations, the speed–Gf relation was low (.30) but the Gf–WM relation was high (.65). The age effect was moderate (.50) and comparable to Swanson for this age phase. It is noted that when both the possible effects of STSS and executive WM on Gf were tested separately, only WM was a predictor. The STSS effect was always very low in both the Swanson and the Berg study (.16). Moreover, the dominance of fluency over pure speed measures, especially in the second wave of the Swanson's study, suggests that the glue underlying these relations is command over processes ensuring mental flexibility when mapping mental units on each other.

Brydges, Reid, Fox, and Anderson (2012). This study involved 215 7- to 9-year-old children. They were 120 7-year olds (57 boys and 63 females) (M_{age} = 7 years 6 months, SD = 3 months) and 95 9-year-old children (53 boys and 42 females) (M_{age} = 9 years 6 months, SD 3 = months). This study is very useful for our purposes because participants were examined by shifting and crystallized intelligence tasks, in addition to speed, working memory, and fluid intelligence tasks used by the other studies analyzed above. Therefore, this study allows disentangling the role of executive processes as such from the role working memory in the transition from the first to the second phase of the conceptual cycle, in the fashion of the Podjarny et al. (2013) study in the previous cycle.

Speed was addressed by three tasks. The classical Stroop task was used to specify inhibition efficiency (difference scores were used between RT to recognizing the color of stars and recognizing the ink color of a different color word). Compatibility reaction time required children judging the length of two lines (same or different). Children first built a prepotent response for the buttons required for same and different judgments and then they responded to the testing block where the buttons were swapped. Their score was the difference between the training and the testing block. In the same fashion, a "go/no-go" task was used where children were first trained to first move their index finger from the left to the right mouse button and back when a soccer ball appeared and then they were tested for their ability to keep their index on the left button when an Australian rules football appeared (the score was the proportion of "no-go" responses).

Three tasks addressed working memory. The backward digit span and letter–number sequencing (children mentally sorted letters and numbers into alphabetical and ascending order and stated the result) tasks from WISC-IV, and a (verbatim) sentence repetition task.

Executive control was examined by three tasks: The Wisconsin Card Sorting Task, the Verbal fluency task (generating names of animals and then names of food as fast as possible) and the letter monitoring task (reading letters from one side of a computer screen while ignoring letters and numbers appearing on the other side and shifting between sides, following a sign).

Fluid intelligence was tested by the Cattell Culture Fair Intelligence test (examining inductive reasoning in series completion, matrices, odd-one out, and topology by items of increasing complexity and abstraction) and the block design from the WISC-IV (requiring children to reconstruct patterns by blocks). Crystallized intelligence was addressed by the vocabulary (picture naming and word definitions) and the information subtests of the WISC-IV (examining general factual knowledge).

The variety of processes addressed and the relative sufficiency of children in each age permits an examination of how inhibition, shifting, working memory, Gf, and Gc relate to each other in each of the two age groups. At the one extreme, the simplest model would be one where the simplest of the processes involved, i.e., inhibition as captured by three tasks used here, exhaustively predicts all other processes. At the other, the most complex model would be a complete simplex model (Jöreskog, 1970) where each higher level process is regressed on the processes residing one complexity level below: inhibition → shifting → WM → Gf → Gc. We first tested this model separately in each age group. The best fitting model for the 7-year olds was close to the most complex of the models above: inhibition predicted shifting (.42), shifting predicted WM (.92) and WM predicted both Gf (.87) and Gc (.60), ($\chi^2 = 84.82$, df = 61, p = .02, CFI = .92, RMSEA = .06) (i.e., the model AIC index (−37.18) was smaller than the two simpler models (−33.84, −36.28) and the full simplex model (−33.18), suggesting that the most parsimonious model is preferable). However, the simplest of these models (model AIC = −38.158 for the first three models and −27.24 for the most complex model) was enough to account for the performance of the 9-year olds: inhibition was enough to predict shifting (1.00), WM (1.00), Gf (.66), and Gc (.77) ($\chi^2 = 83.84$, $df = 61$, $p = .03$, CFI = .90, RMSEA = .06). This model was tested in a 2-group analysis where all measurement–factor relations were constrained to be equal across the two age groups and found to have a very good fit ($\chi^2 = 125.02$, $df = 104$, $p = .08$, CFI = .96, RMSEA = .04).

This dominance of inhibition in the 8–10 years phase seems equivalent to the dominance of inhibition in the 4–6 years phase found above. It seems that in the alignment phase of each cycle the common executive core is effectively integrated into processing, strengthening the relations between working memory and problem solving.

Some of the studies presented above are appropriate for inclusion in multiple groups modeling that would test the equivalence of constructs across studies. One of these analysis involved the third wave of the van der Ven et al. (2012) study ($M_{age} = 7.5$ years) and the first age group of the Brydges et al. (2012) study ($M_{age} = 7.5$ years). In this model, one congruent and two incongruent measures from van der Ven et al. and all three speeded performance measures from Brydges et al were used to index speed; all three working memory measures from van der Ven et al and three working memory tasks from Brydges et al were used to index working memory. Finally, all three executive control tasks from each study were used to index cognitive flexibility. Also, in line with our initial models, working memory was regressed on speed and executive control was regressed on both speed and working memory in both models. Moreover, all measurement–factor and all factor–factor relations were constrained to be equal across the two groups. Despite this very strict assumption of complete equality, the fit of the model was acceptable, ($\chi^2 = 104.67$, $df = 62$, $p = .00$, CFI = .91, RMSEA = .06). According to Lagrange test for releasing constraints (Bentler, 2006), one of the measurement–factor relations constrains did not hold (that the WCST task was equally related with the executive control factor across the two groups). Releasing this constraint resulted in a significant improvement of the model fit ($\chi^2 = 89.73$, $df = 61$, $p = .01$, CFI = .91, RMSEA = .05 $\Delta\ \chi^2 = 14.94$, $p < .001$). In both models, executive control was significantly related to both speed (.44, and .80 in van der Ven et al. and Brydges et al., respectively) and working memory (.38 and 45, in van der Ven et al. and Brydges et al., respectively).

A second multiple groups analysis involved the fourth wave from van der Ven et al. (2012) and the 9-year-olds from Brydges et al. (2012). In addition to the measures involved in the analysis above, this model also involved the mathematics and the Raven score from the van der Ven study and the Cattell and the block design scores from the Brydges et al study to index Gf. Also, in addition to the constraints above, the present model included across groups constraints for the Gf measures. The fit of this model was again good ($\chi2 = 129.36$, $df = 98$, $p = .02$, CFI = .94, RMSEA = .05). As expected for this age group, Gf was highly related to working memory in both the van der Ven (.84) and the Brydges study (.67). Therefore, there was strong equivalence across the studies in the constructs standing for speed, working memory, executive control, and Gf.

1.3. The shift from concepts to principles

Kail (2007) and *Fry and Hale (1996)*. These are two of the most highly cited studies in the developmental literature concerning the speed–WM–Gf relations. Kail's (2007) study involved 277 participants (137 males and 140 females) from 6 to 12 years of age. All but the 6–7 years old children were tested with five tasks. Two tasks tested speed of processing: In the visual matching task children circled the identical digits (2) in each of 60 rows of six digits. In the cross out task children crossed out the 5 of 19 figures matching a target figure in each of 30 rows. Two tasks addressed working memory: In the reading span task, children read brief sentences ending with a noun, indicated if it is true or false, and at the end of each set they recalled the nouns in order (1 to 5). In the listening span task children listened rather than read the sentences. A set of 30 (odd-numbered) problems were selected from Raven's Standard Progressive Matrices to measure Gf. Six- and 7-year olds received only the Cross Out, the Listening span, and the Raven's matrices.

The study by Fry and Hale (1996) included a total of 214 participants (96 males) drawn from second through seventh grade and college. These participants were examined by four tasks addressed to speed, four tasks addressed to working memory, and the Raven test. Of the tasks addressed to speed and working memory two from each set were identical to the tasks used by Kail. Thus, to increase power, the two data sets were joined into one involving the five common tasks. The integrated data base included four age groups: 6–7 years ($N = 91$, $M_{age} = 7.00$ years, $SD = .63$ years): 8–10 years ($N = 216$, $M_{age} = 9.59$ years, $SD = .88$ years), 11–13 years ($N = 119$, $M_{age} = 11.92$ years, $SD = .58$ years), and 14–20 years ($N = 109$, $M_{age} = 17.44$ years, $SD = 2.44$ years).

The model was tested in a four-group analysis, one for each of the four age groups specified above. To identify the factors for speed, WM, and Gf in the younger age group, where there was only one indicator for each construct, a dummy factor was created for each construct by fixing the factor-measure relation to 1. In the three older age groups the factors for speed and WM were identified in reference to the pair of measures addressed to each of them. Gf was identified as a dummy factor fixed to 1 on the Raven score. Across groups equality constraints were imposed for each of the two measures that were free to be estimated.

The model above was fit to the integrated data base under the assumption that all free measurement–factor relations were equal across the three age groups. The fit of this highly constrained model was good ($\chi^2 = 61.60$, $df = 30$, $p = .01$, CFI = 1.00, RMSEA = .08, SRMR = .06). The relations were fully consistent with expectations. That is, in the 6–7 years age group the speed–Gf relation was very high (.91) and the WM–Gf relation was non significant (.31). The total age effect was high (.58). In the 8–10 years age group, the speed–Gf relation was non-significant (−.06) but the WM–Gf relation was high (.64). The total age effect was low (.23) but significant. In the 11–13 years group the speed–Gf relation was again very high (.83) and the WM–Gf relation was non significant (.26). The total age effect was also low but significant (.26). Finally, this pattern was inverted again in the 14–20 years age group: the speed–Gf became non significant (.15) and the WM–Gf (.91) rose drastically. The total age effect was still significant but low (.14).

Nettlebeck and Burns (2010). This study involved 478 participants (288 males and 190 females), organized in four non-overlapping age groups: 8–10 ($N = 118$, $M_{age} = 9.49$, $SD = .64$), 11–13 ($N = 84$, $M_{age} = 12.86$, $SD = .69$), 14–30 ($N = 105$, $M_{age} = 20.14$, $SD = 5.36$), and 31–80 years ($N = 169$, $M_{age} = 53.31$, $SD = 16.55$).

Speed was addressed by five tests: Digit symbol from the Wechsler Adult Intelligence Scale, visual matching from Woodcock–Johnson Psycho-Educational Battery—Revised, Inspection time (choose the shorter of two lines, at decreasing SOA by 17 ms.), simple reaction time (releasing a home button in response to a light onset as fast as possible), and odd man out simple decision time (three of eight possible lights were illuminated, with two adjacent and one further away; participants responded to the latter).

Three tests addressed working memory. Mental swaps required inspecting objects on three locations, mentally swap them in pairs and recall from 1–4 swaps. In the picture recognition task participants first saw a set of pictures (1–7), then a second set (2–6, 1–4 common with the first set) and they indicated which pictures of the second set were in the first set. The forward digit span (1–9 items) was also given.

Gf was assessed by the Cattell Culture Fair Test mentioned above.

To implement the assumption that tasks indexed factors similarly across groups the measurement–factor relations were constrained to be equal across the four age groups but the between factor relations were allowed to vary freely. The relations completely conformed to expectations in the first three age groups and shed light on the nature of adulthood as a developmental phase in the life-span development. Specifically, at the 8–10 years phase, the speed–Gf relation was nil and the WM–Gf relation was high (.71). The age effect was .27. This pattern was inverted in the 11–13 years phase: the speed–Gf relation rose drastically (.84) but the WM–Gf vanished. The age effect in this period was considerably higher (.44). In the 14–30 years phase both relations were significant but the WM–Gf relation (.74) was considerably higher than the speed–Gf relation (.51). The age effect dropped again (.25). In maturity, the relative magnitude of relations was inverted again: the speed–Gf was .86, the WM–Gf was .47, and the age effect was −.70. The speed–WM relation was always high (always > .8).

To examine comparability between the combined Kail (2007) and Fry and Hale (1996) studies and the Nettelbeck and Burns study a multiple groups analysis was run which included six groups: the 8–10, 11–13 and 14–adults group from each of the two sets. All tasks from each study used in the models above were also used here. To examine structural equivalence the following across-groups equality constraints were imposed. First, the measurement–factor relation of each of the free parameters associated with a factor in the Kail-Fry and Hale study and the closest task used in the Nettelbeck and Burns study to address the same construct (i.e., visual matching for speed, mental swaps for working memory, and matrices from the Cattell test for Gf) were constrained to be equal across the six groups included in the model. Second, all factor–factor relations of same-age groups were constrained to be equal across the two studies. These are very strict constraints assuming construct invariance and same-age population invariance across the various studies. Despite these constraints and the very large sample sizes of the combined studies, the fit of the model was good ($\chi^2 = 251.13$, $df = 107$, $p = .00$, $CFI = 1.00$, $RMSEA = .09$). The speed–Gf relation (.52 and .29 in the 11–13 years group of the Kail-Fry and Hale and the Nettelbeck and Burns study, respectively) and the WM–Gf relation (.60 and .94 in the 8–10 and .52 and .99 in the 14-adults group in the Kail-Fry and Hale and the Nettelbeck and Burns study, respectively) in the various groups were very similar to those obtained in the separate models above and very close to expectations for each of the various age groups. Obviously, the convergence between studies is notable.

Demetriou et al. (2005). This is part of the cross-cultural study mentioned above, which focused on the transition from childhood to adolescence (Demetriou et al., 2005; Kazi, Demetriou, Spanoudis, Zhang, & Wang, 2012). For the present purposes we used the Chinese sample to examine if the expected patterns for these age phases hold in another culture. This sample included a total of 120 participants equally drawn among 8 ($M_{age} = 104.43$ months, $SD = 1.78$), 10 ($M_{age} = 130.70$ months, $SD = 2.64$), 13 ($M_{age} = 154.80$ months, $SD = 2.54$), and 15 ($M_{age} = 180.20$ months, $SD = 1.86$) year olds. These participants lived in a large city in North Eastern China.

Speed of processing was examined by three Stroop-like tasks described in Demetriou et al. (2005, 2013). Participants responded to three congruent and three incongruent stimuli in each of three domains (i.e., verbal, numerical, and figural stimuli). These tasks were similar to those used by van der Ven et al. (2013) and Brydges et al. (2012). Working memory was represented by three scores standing for performance to phonological STSS (word and digit forward span tasks), visuospatial STSS (reconstruct arrangements of geometrical figures by choosing the figures seen before and placing them at the right place and orientation), and executive processes (e.g., store sentences referring to a number of objects and recall either the objects or the number according to instructions—the father bought four toys). Gf was represented by three scores standing for performance on verbal (verbal analogies and deductive syllogisms), spatial (mental rotation and coordination of perspectives), and quantitative reasoning tasks (numerical analogical and logical relations between numerical operations).

To test the model, the two younger age groups were pulled together to form the 8–10 years group and the two older age groups were pulled together to form the 13–15 years group. This allowed to run a 2-group analysis where all measurement–factor relations were constrained to be equal across groups and the between factor relations were left free to vary. The model was tested twice, using reaction times to the congruent conditions of the Stroop-like tests in the first run and the reaction times to the incongruent conditions in the second run. This would show if inhibition is differentiated from sheer speed. According to the prediction, the WM–Gf relation must be higher than the speed–Gf relation in both groups, because they both fall within the later part of their cycle. This is what was found in the first run of the model, when reaction times to the congruent conditions were involved: In the 8–10 years group the WM–Gf relation was lower than expected (.39) but considerably higher than the speed-Gf relation (−.20). In the 13–15 years group the pattern was fully consistent with expectations and comparable with all other studies for this age group (.62 and −.26, respectively). In the second run of the model, when reaction times to the incongruent conditions were involved, the relations stayed practically unchanged in the younger group (i.e., .36 and −.23 for the WM–Gf and the speed–Gf relation, respectively). However, there was a drastic change in the older group. Specifically, the WM–Gf relation remained practically the same (.68) but the control–Gf relation increased extensively (−.73).

Taken together, the results of the two models suggest that inhibition processes are more important than sheer speed in the 14–16 years alignment phase of the principles cycle. This finding is consistent with the findings above concerning the alignment phases.

Leonard et al. (2007). This study is part of a larger project which examined the effects of various factors of information processing on language development. The present study included 204 14-year old adolescents ($M_{age} = 13.91$ years; $SD = .40$). The majority (166) of them had typical non-verbal intelligence (mean total WISC-III IQ 99.8; $SD = 10$). This score was low among the rest ($Mean = 77.9$; $SD = 4.8$). Language ability was typical in about half of them (126) and low among the rest. Thus, this study is suitable for testing our prediction for the last phase of development specified by the model.

Speed was measured by a large array of tasks. For the present purposes we used only those tasks that were similar to the tasks used in the other studies to address speed. Specifically, a visual search task examined speed in searching a 5-stimulus array in order to identify if a target stimulus was present. A mental rotation task examined speed in judging which of three identical figures differing in orientation matched the orientation of a target figure. The perceptual matching task examined speed in judging if two pictures presented simultaneously were physically identical. Finally, a category membership task examined speed in judging if two objects belonged to the same category.

Four tasks addressed working memory. In the Auditory Working Memory task (drawn from the Woodcock–Johnson III test) words and digits are presented interchangeably and the participant needs to recall them separately, in a word and digit sequence in presentation order. The Nonword Repetition Task assessed phonological memory in recalling nonsense words in presentation order. A simple listening span task examined the ability to recall the last word of sequences of sentences, according to Daneman and Carpenter (1980). A more demanding listening span task examined recall of words according to a certain grammatical rule.

Performance IQ was examined by the block design and the picture completion tests. Language ability was examined by tasks addressed to expressive and receptive vocabulary, and discourse (grammatical) recall and understanding.

It is predicted that working memory would be the dominant predictor. The model was tested in two versions. In the first version, there was a speed factor, a working memory, and a general intelligence (G) factor defined by the speed, the working memory, and the IQ and language composite scores, respectively. In this version of the model, the speed–G relation was significant but low (.21) but the WM–G relation was high (.75), in line with our prediction. In the second version, the language score was dropped so that we can test the relation of speed and working memory with performance IQ, which is a good approximation of Gf. In this model, the WM–Gf relation was not basically affected (.72) but the speed–Gf relation rose considerably (.42). This pattern is comparable to the pattern obtained from the Nettelbeck study for this age phase.

Rijsdijk, Vernon, and Boomsma (1998). This is a study of the genetic basis of the speed–IQ relations. It involved 213 16-year-old adolescents ($M_{age} = 16.13$ years, $SD = .56$). Speed was examined by a simple reaction time (respond to a letter or a digit) and a choice reaction task (recognize if a stimulus is either a letter or a digit). Working memory and Gf were examined by WAIS tasks (i.e., the digit span and the performance tests, respectively). Factors were created for speed, WM, Gf, and Gc. The fit was excellent ($\chi^2 = 42.09$, $df = 38$, $p = .30$, $CFI = .99$, $RMSEA = .02$). As expected, the speed–WM was significant (−.42), the speed–Gf (−.10) was very low and the WM–Gf relation was high (.62). Gc was significantly related to both WM (.57) and Gf (.45).

2. Discussion

It is notable that our predictions about the recycling patterns of speed–Gf and WM–Gf relations were borne out by so many different studies, especially if the structural equivalence of these studies is taken into account (see Fig. 2). These patterns provide support for an integrated developmental–differential theory of intelligence that would explicate why Gf changes coalesce with speed at the beginning of developmental cycles and with WM changes at the end. Gf undergoes three types of change: representational, inferential, and complexity. To accommodate these patterns, an overarching theory would have to account for all three types of change and specify how they relate with speed and working memory in development. Below we will first outline this theory and compare it with other cognitive development theories. Then we will explicate the interactions between processes suggested by these patterns.

2.1. ReConceP and developmental theories

Psychometrically speaking, ReConceP corresponds to the Gf factor abstracted from performance on the age-appropriate tasks used in the various studies. Developmentally speaking, the ReConceP sequence specifies the representational, inferential, and processing possibilities available at successive age phases, highlighting how mental age is expressed in each phase (Demetriou, Spanoudis, & Shayer, 2013; Demetriou, Spanoudis, Shayer, Mouyi, et al., 2013). Thus, changes along the ReConceP sequence reflect increases in mental fluidity because each next ReConceP phase produces a new representational unit that is semantically richer, better storable, and amenable to faster processing than the unit of the previous phase. Moreover, the new unit allows viewing the representations of lower levels from this unit's perspective. This enhances representational and inferential options because alternative perspectives and integrative tools may be drawn from the current or lower levels to bear on the concept or problem at hand. Naturally, increasing mental fluidity is reflected in increasing problem solving and understanding possibilities addressed by psychometric tests of intelligence.

From birth to 2 years representations depend largely on observational and action episodes merged with ongoing experience rather than on mental states disconnected from experience. Alignment of episodic representations (e.g., seeing an object in different locations) in the second year protracts them in time, yielding organized problem solving skills, such as means–end actions, and mental tokens of them, such as in object permanence. At about 2 years global mental representations emerge which are mental analogues of these interlinked observational and action episodes. Iconic representations (e.g., "cat", "dog") dominate at the beginning but other symbolisms may be used, such as language or pictures. Global representations initially stand for experiential episodes and function en block yielding inferences based on the episodic flow of events. Plausible inductions complete activated experiential episodes without constraining each other, if not aligned. Alignment of global representations in the next phase optimizes inductive choices because it allows comparisons of represented events, allowing pragmatic reasoning (e.g., "We agreed I will play outside if I eat my food; I ate my food; I go outside to play") (see Kazi et al., 2012).

At the beginning of the next cycle, the relations between representations come into focus, yielding generic concepts (e.g., "animal", "bird", etc.) and systematic inference (e.g., "it has four legs, so it is an animal"). Thus, at this early phase, encodings of the relations between representations are explicitly represented, providing the mental ground for the dominance of language in mental representation. Other arbitrary forms of representation are now possible, if the underlying relations are conducive to them, such as the mental number line in quantitative reasoning (Dehaene, 1997). Later in this cycle, alignment of generic concepts yields conceptual hierarchies (e.g., "cats and dogs and birds are all animals") and explicit grasp of their logical (e.g., "animals are more than any class included in them") or semantic relations (e.g., "she flies like a bird", "he jumps like a cat", etc.).

Explicitly representing logical and semantic relations yields the principles of the next cycle. Principles may be seen as conditional representations defining acceptable relations between concepts and inferences (Demetriou, Spanoudis, & Mouyi, 2011; Demetriou, Spanoudis, & Shayer, 2013; Demetriou, Spanoudis, Shayer, Mouyi, et al., 2013). Thus, they enable thinkers to view systems of representations from the point of view of each other. Explicit analogical and metaphorical reasoning at the beginning of adolescence are examples of conditional representations. Alignment of conditional representations allows complex hypothetico-deductive thought. For example, recognition of logical fallacies, such as affirming the consequent, is now possible, because complementary representations can be stringed along a validity principle and evaluated for consistency.

All theories of cognitive development may be aligned along ReconceP, regardless of their domain of emphasis. For instance, Piagetian transitions correspond to the cycle and phase transitions of ReConceP. Piaget emphasized the logical achievements underlying these transitions rather than representational changes as such. The logic of displacements, functions, classes and relations, and symbolic logic were associated with the four major stages of sensori-motor, preoperational, concrete, and formal thought, respectively (Piaget, 2001). Obviously, logical reasoning does develop with ReConceP, as explained above. However, growing mastery of logical relations is a side-effect of representational reorganization and inter-linking rather than the driver of it. For instance, recent research shows that heuristic thought develops in parallel with logical reasoning (Morsanyi & Handley, 2011). Progress along ReConceP enhances heuristic thought, often seemingly at the expense of logical reasoning, because it adds options in inter-relating representations. Increased logicality is just one of the options. That is, any of the two approaches, logical-analytical or heuristic processing, may dominate, if the representational possibilities available meet situational requirements of the problem at hand. Therefore, a model of intellectual development based on logical development is not sufficient to account for changes that are not reducible to conventional rules of logic. This supports our prioritization of representational change in explicating ReConceP.

The neo-Piagetians emphasized the information processing complexity underlying ReConceP, because representations at higher levels are inherently more variable and differentiated than at lower levels (Case, 1985; Fischer, 1980; Halford et al., 1998; Pascual-Leone, 1970). However, specifying complexity is not enough to account for ReConceP. The alternating patterns of speed–Gf and WM–Gf relations suggest that there are procedural and semantic aspects of representations that differ between phases. Along this line, Bruner (1966) and Fischer (1980) did emphasize symbolic changes associated with intellectual development. Bruner highlighted the change from enactive to iconic representation at 2 and from iconic to symbolic (verbal) representation at 7 years. Fischer pointed to abstractions attained at 11 years as a component of representation, in addition to Bruner's representational systems. Thus both pointed to the fact that representations at each next successive cycle have "symbolic preferences" for systems better able to express their level-specific peculiarities than others. For instance, global representations of the representational cycle "prefer" mental images, because they are close to the episodic nature of the experiences they represent. Generic concepts of the conceptual period "prefer" language, because it can express common properties and relations. Principles prefer, in addition to language, abstract symbol systems such as logical or mathematical symbolisms, because they can encapsulate relations between relations. Each of these systems can better express the episodic, the declarative, and the conditional nature of representations of the three cycles, respectively.

Along this line, there is evidence showing that visuo-spatial working memory develops from 1 to 4 chunks from 4 to 8 years, when it basically levels off. Verbal working memory wavers around 2 chunks from 4 to 8 years, when it takes off to approach the ceiling of 4–5 chunks at 13 years (Demetriou, Spanoudis, & Shayer, 2013; Demetriou, Spanoudis, Shayer, Mouyi, et al., 2013; Riggs, McTaggart, Simpson, & Freeman, 2006). In line with this evidence, Alloway, Gathercole, and

Pickering (2006) showed that although all components of working memory are in place from the age of 4 years, the links between the visuo-spatial component and the central processing component is stronger in the 4–6 years phase than later. Interestingly, Pickering (2001) showed that recoding of visually presented information into a phonological form appears at the age of 8 years, which coincides with the shift from visual to verbal working memory development. Regrettably, there is not much research examining the development of working memory involving abstract conditional-type representations. However, there is some evidence showing that although there is not much difference in how 6–7-year-old children handle visual load of 3–4 units, 12–13-year-old preadolescents do have an advantage when load increases to 5–6 units, suggesting a shift in selective attention and information filtering (Cowan, Morey, AuBuchon, Zwillling, & Gilchrist, 2010).

2.2. Explicating recycling

The recycling of representations along ReConceP needs special attention because it is related to the alternating cycles of speed–Gf and WM–Gf relations. It is notable that most theories of intellectual development assume some kind of recycling (Case, 1985; Fischer, 1980; Pascual-Leone, 1970; Piaget, 1970). These theorists recognized an “early” and a “late” phase within each major developmental period, assuming that representations are unstable and uncoordinated early after each major transition but they become increasingly consolidated and integrated on the way to the next transition. In fact, empirical research using many different kinds of tasks did validate this early-late phase interchange throughout the 8-phase sequence (Shayer, Demetriou, & Pervez, 1988; Shayer, Küchemann, & Wylam, 1976).

Case (1985) was probably the first to recognize the difference in the role of speed and working memory at the two phases within developmental cycles. He claimed that automation in executing level-specific operations, such as counting in the dimensional level attained at 6–7 years, is associated with increased short-term storage space (STSS) for related items, such as the digit span. In turn, increased STSS may be used for the integration of level-specific representations into more complex structures. Anderson (1992, 2001) also differentiated between speed and working memory as dimensions of intellectual functioning. He posited that speed does not change. The speed changes with age are only phenomenal because they reflect changes in other processes such as response selection. However, speed does vary across individuals, causing individual differences in Gf within age groups. The main driver of age related change in Gf is improvement in the control of interference, which is the core of the central executive in working memory.

At the beginning of cycles processing speed may increase for a number of reasons. On the one hand, thought in terms of the new mental unit itself may compress the time requirements of mental processing. For instance, handling abstractions may provide shortcuts to mental process as compared to spatially constrained search in visuospatial working memory (Paivio, 1991). On the other hand, command of the new representational unit improves at the beginning of cycles and thinking in terms of it proliferates fast to new content. Increasing speed may reflect both increased mental efficiency that is inherent in the new mental units of a cycle and improvement in command and generalization. Thus, fast changes in processing speed at the initial phase of each cycle may reflect any combination of these changes in representations and their use.

Later in the cycle, when 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 working memory, rather than plain storage, that was found to predict Gf changes in the second phase of each cycle. In fact, the studies analyzed here (Astle et al., 2013; Bernstein et al., 2007; Brydges et al., 2012; Podjarny et al., 2013) which involved various measures of executive processes as such and working memory showed these processes are equally powerful predictors of higher level cognitive processes, such as dual representation, ToM, and Gf, in the alignment phases. Moreover, the patterns uncovered by the Brydges et al. (2012) study showed that on the verge of transition between the first and the second phase of the conceptual cycle, at 7.5 years of age, working memory is needed to predict Gf and Gc. Two years later, well in the second phase, inhibition alone, the core of executive processes, was enough to account for all other higher level processes. This finding explains why working memory covaries extensively with intelligence throughout development from 4 years to adulthood but it does not account for transitions along ReConceP (Demetriou, Spanoudis, & Shayer, 2013; Demetriou, Spanoudis, Shayer, Mouyi, et al., 2013). That is, it suggests that the major building block of changes in working memory and Gf is a core executive program enabling the binding of information in both working memory and inferential processes. This core program allows children to distinctly represent a minimum of 2–3 thoughts, alternate between them, and arrange them in time to meet a goal. This is attained at 4–6 years, when it is first transcribed into working memory. The tasks used in the three studies addressed to 4–6 years old children (Podjarny et al., Astle et al., and Bernstein et al.) imply in this phase this core program is based the mastery of inhibition processes allowing the deactivation of representations or responses. Later, in primary school this core is transcribed into conceptual spaces. The tasks used in the studies by Swanson, Berg, and Bridges et al. suggest that in the 8–10 years phase, fluency is added to representational-action inhibition processes, which allows children to steer their way into and across conceptual spaces. There is lack of research into how this core program is expressed in adolescence. This interpretation lends support to theories assuming that command of interrupt-executive processes is a powerful cause of intellectual development (Anderson, 2001; Pascual-Leone & Johnson, 2011).

However, the present findings do not lend support to the claim that speed is not a developmental factor. These findings suggest that speed is a powerful developmental index of major developmental transitions in Gf. Within these phases speed may also be an index of individual differences in the rate of implementation of these transitions. However, ascribing speed the status of a powerful developmental marker of changes in higher level cognitive processes does not imply any direct causal relation of any direction. It is stressed that speeded performance measures which did or did not explicitly require inhibition were very highly (>.9) inter-related and their effects on WM and Gf were very similar, suggesting that even very simple reaction time tasks always activate some kind of mental control (Stankov & Roberts, 1997). The same holds for short-term memory tasks, which always require some executive control. In line with this assumption, recent research on the genetic factors underlying the speed–Gf relation found no causal relation between them. Thus, other factors are operating which cause changes in both of them (Luciano et al., 2005).

2.3. Limitations and future directions

However notable the convergence of the various studies is, it is recognized that variations across studies in the tasks used to address each of the main constructs of interests may blur or confound relations or trends. To some extent, this limitation was compensated by multiple groups modeling where equivalence between studies was statistically imposed. However, new studies especially designed to measure the constructs of interest at the successive developmental phases are needed to validate the present findings. It is a truism in developmental research that nothing can replace longitudinal evidence. Ideally, then, the patterns observed here would have to be examined longitudinally to see if the strength of speed–Gf and WM–Gf relations do alternate with growth in the same individuals. Special attention is drawn, on the one hand, to the lack of research in infancy that would allow us to examine if the patterns observed here also hold in the first three years of life. On the other hand, research should examine if negative changes in adulthood would result in a gradual inversion of the strong WM–Gf–weak speed–Gf relation, rendering changes in speed the precursor of these negative changes, as suggested by the Nettelbeck study. Also, it should be apparent that the crucial factor driving these patterns is not age as such but the condition of the cognitive processes involved. Therefore, it would also be important to experimentally induce the patterns observed here in learning experiments that would independently manipulate each of the main processes involved, i.e. processing efficiency and control, representational capacity and mental flexibility, and inferential processes. Finally, research of brain development suggests that the cycles identified here correspond to cycles of brain development (e.g., Thatcher, 1994). Research would have to explore what changes in the brain are related to transitions across ReConceP and what brain functions supports the mental possibilities associated with each ReConceP phase.

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