Developmental intelligence: From empirical to hidden constructs

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ABSTRACT

This article answers some of the criticisms and suggestions of the three commentaries. We showed, in agreement with Coyle, that (i) variability is indeed distinct from speed, (ii) they both additively reflect processing efficiency and (iii) that they differentially relate to WM and gf during development. In agreement with Kail, we showed that developmental intelligence and psychometric intelligence are (i) related but distinct, they additively contribute to school learning and (iii) their role varies with developmental phase. Finally, in agreement with Pascual-Leone, we proposed a number of higher level hidden constructs to account for the data patterns observed between empirical constructs, such as speed, variability, WM, and reasoning.

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1. Introduction

Intelligence is an elusive construct because, contrary to Boring (1923), there is much more in it than what the tests measure: processing efficiency, attention, executive control and mental flexibility, working memory, inference (inductive, deductive, and abductive), planning, learning, and decision making. Research in different disciplines or traditions focused on some of these components but integrative research is rare. The psychometric tradition emphasizes individual differences in learning and dealing with novelty. Cognitive researchers focus on the mental processes in learning and thinking. Developmental researchers study their development. In our research we attempt to integrate the three traditions in a comprehensive theory that would specify the mental processes involved in intelligence and account for their organization and development.

The target article (Demetriou et al., 2013) presented three studies which investigated how speed of processing, working memory, and inference (i.e., deductive and inductive reasoning and problem solving in various domains, or gf), develop and interact from 4 to 16 years of age. We showed that processes are organized in two major levels, an efficiency level defined by speed and control and a representational level defined by WM and gf, which are increasingly differentiated with development. Speed increases with age from 4 to 13 years, leveling off thereafter (until young adulthood), but its relation with gf is mediated by WM. WM always relates to speed and gf, but it accounts mainly for individual differences in gf rather than developmental changes in it. All processes develop in cycles marked by changes in the nature and integration of representations. Changes in speed reflect major changes in the nature of representations and changes in working memory reflect changes in their integration.

We are honored by the decision of Douglas Detterman, the Editor of Intelligence, to invite commentary on this paper. And we are grateful to our commentators, Thomas R. Coyle, Robert V. Kail, and Juan Pascual-Leone, for their constructive commentaries. They all raise important issues which may move the field forward, if satisfactorily answered. Some of them are empirical and some are conceptual. Empirical issues are resolved by evidence. Conceptual issues may be resolved through constructs that would enhance our understanding of phenomena and open new empirical issues to be resolved by
further research. In this rejoinder we will first respond to the empirical issues and then elaborate on the conceptual issues. Coyle (in press) suggests that we may have underestimated the role of speed because we used rather simple tasks and ignored variability of reaction times (RTSD). Following Jensen (1998, 2006), he suggested that RTSD may be an important aspect of processing efficiency because it reflects neural efficiency in information processing better than speed. Kail (in press) suggests that the theory must expand to cover younger and older age spans than those covered by the target article. Moreover, he proposes that the theory must be tested in more real-life situations, such as school learning. Pascual-Leone (in press) suggests that we need to move beyond empirical demonstrations of patterns and relations to underlying hidden constructs than may unify the processes involved and allow the discovery of underlying integrative powers. We will answer these issues in turn.

2. Speed and variability in processing efficiency and development

Speed of processing is an index of neural efficiency in registering and processing information (Jensen, 1998). Individual and developmental differences in psychometric intelligence reflect, to a significant extent, differences in the quality of information processing. This is the reason why speed is a relatively good predictor of both individual and developmental differences in intelligence. In the target article we showed that the power of speed wanes with age and when it is strong it is mediated by working memory, becoming redundant as a predictor when working memory is taken into account. We suggested that this is due to the fact that speed and WM share common components, such as attention. Also, WM tasks are to some extent speeded tasks because storage and recall of information occur under time limitations. Coyle, based on Jensen (1998, 2006), suggested that variability of speed of processing may be a distinct, if not a better, index of neural efficiency because it reflects processing cohesion and control: the lower the better.

We used the measures of Studies 2 and 3 to investigate the role of variability. Children in Study 2 were examined by five types of speeded performance tasks of systematically increasing complexity: Simon-like tasks requiring location identification (Speed, 2 tasks), Stroop-like tasks requiring letter or digit recognition (i) without (Perceptual Discrimination (PD1), 4 tasks) and (ii) with interference (Perceptual Control, PC, 4 tasks), and object recognition tasks requiring object recognition (i) without (PD2, 3 tasks) (ii) and with conceptual interference (Conceptual Control (CC), 3 tasks). All tasks are described in detail in Demetriou et al. (2008), (2013). We estimated variability according to the method proposed by Jensen (2006). That is, we first estimated the individual sd for each of the five task groups above and then estimated variability according to the Eq. (1) below:

$$\text{Mean RTSD} = \sqrt{(SD_1)^2 + \ldots + (SD_n)^2}/n.$$  

To test if variability is a factor of mental efficiency in addition to speed and working memory, we tested Model B described in the target article (Demetriou et al., 2013) including variability, in addition to the other factors. Specifically, this model included three indexes of speed (PD, PC, and CC), three indexes of variability (the SD for each of these measures), three indexes of working memory (visual WM, and two versions of Case’s working memory task for numbers), and two indexes of gf (inductive and deductive reasoning). The model is shown in Fig. 1 (with fit indexes). It can be seen that speed and variability were regressed on age, WM was regressed on speed and variability, and gf was regressed on speed, WM, and variability. This model was first tested on the total sample which included 395 children (about equally drawn among first through sixth primary school grade (mean age 6.6 to 11.6 years, respectively)). The model was also tested in a 2-group analysis, where the first group included grades 1–3 (199 participants) and the second included grades 4–6 (196 participants). In this model, the relations of variables to factors were constrained to be equal across the two groups and the between factors relations were allowed to vary freely.

In the model applied on the total sample, the effect of variability on WM (−.45) and gf (−.23) was significant. In the 2-group model, in the 6–8 years old children, the effects of both variability (−.43) and speed (−.49) on gf were significant and relatively high. However, in the 8–11-year olds, both effects on gf were low (−.22 and −.20, respectively) but the effect of WM on gf (.43) was much higher. Interestingly, however, variability effects on WM were about the same in the two age groups (−.41 and −.39, respectively) and much higher than the effects of speed (−.17 and −.15, respectively). Therefore, variability indeed is, as suggested by Coyle, a factor influencing WM and gf on top of speed. In line with the theory proposed in the target article, these effects are stronger in the 6–8 than in the 9–10 years of age phase, suggesting that important changes in mental cohesion occur in the first rather than in the second phase of a period, when a new mental unit is formed.

We tested these relations on the measures of Study 3, which covers development in adolescence. In this study, variability was estimated over four groups of compatible and incompatible Stroop-like tasks, each including three tasks (dominant stimulus recognition-compatible, dominant geometric figure recognition made of the same figure, component figure (letter) recognition-interference from the dominant figure (letter), component figure (letter) recognition-interference from the dominant figure (number)). The model described above was tested on the performance attained by Cohorts 2, 3, and 4 at second (when they were 11, 13 and 15 years old) and third testing (when they were 12, 14 and 16 years old). The relations obtained are shown in Fig. 1. It can be seen that the effects of speed on WM (−.70) and gf (−.61) were strong. Also, the effect of WM on gf was very high (.79). However, the effects of variability on WM (−.18) and gf (.0), were very low, suggesting that cognitive changes in adolescence are not associated with variability. Fig. 2 shows that this is due to the fact that no important changes occur in variability after the age of 11 years. It can be seen that variability decreases in two steps, from 6 (.36 s) to 8 years (.23 s) and then again from 10 (.22 s) to 11 years (.16), settling at this level thereafter. Obviously, changes in variability co-occur with changes in the kind of concepts gf can handle.

In conclusion, the appearance of speed and variability as distinct factors with different effects on WM and gf supports
Coyle’s suggestion that speed and variability are distinct indexes of processing efficiency. They both change with age but their role as predictors of WM and gf is not the same. Variability relates to WM more than speed, probably reflecting executive control that is a factor of cohesion in handling information in WM. That is, low variability over different speeded tasks indicates better mastering of executive attention mechanisms underlying performance on these tasks. These very mechanisms are part of performance on WM tasks as well. It is worth noting here that the correlation between variability as defined here and the difference between performance on simple and complex working memory tasks, although low, are significant in all three studies (circa .2), suggesting that variability decrease reflects changes beyond the speeded performance tasks. This finding highlights why variability was also a significant factor for gf change in phases of representational change. Its role wanes when it peaks because mental construction after this point requires other mechanisms, such as learning, to be discussed later.

3. Mapping mental processing-school achievement relations

Kail (in press) is right in pointing out that integration of research paradigms must be based on empirical evidence exploring how constructs in different paradigms relate to each other. In this line, with Case (Case, Demetriou, Platsidou, & Kazi, 2001) we showed that constructs measured in cognitive developmental research and psychometric research of intelligence are closely related. The very same broad factors (i.e., quantitative, spatial, causal, inferential, and social reasoning), all related to a higher-order G factor, underlie research in both paradigms. Moreover, the G factors, when separately extracted from performance on cognitive developmental and psychometric tasks correlated highly (.62).

In the present context, exploring the relations between the mental processes studied in the target article and school achievement is possible because we ran studies where we used the tasks employed in the target article studies together with measures of performance in three school subjects: Mathematics, science, and Greek. We asked the teachers of
these subjects to rate each student (on 7-point scale) in three aspects of their performance: Understanding complex concepts, ability to learn, and actual performance. The model tested is shown in Fig. 3. It can be seen that gf is significantly related to all three school subjects, although the relation with science (.53) is higher than with Greek (.45) or mathematics (.36). Interestingly, the relation with WM is higher in all cases (.59, .74, and .73, for science, Greek, and mathematics, respectively). The effect of speed, although always significant, was much lower and only indirect (−.26, −.22, and −.17).

A second study addressed to adolescents from 12 to 17 years of age included, in addition to the measures above, the WISC-III test. In this model, there was an IQ factor related to verbal IQ and performance IQ and a cognitive factor related to our cognitive development test. These two factors were related to a G factor. Obviously, this grant G represents developmental processes captured by our cognitive development battery and processes related to individual differences in intelligence captured by the WISC test. In this model, the effects of G on school science (.93), Greek (.67) and mathematics (.83) were very high. The effect of WM was much lower but significant in science (.20) and Greek (.17) but not in mathematics (.12). Expectedly, there was a strong effect of verbal IQ on Greek (.72). To decompose the effects of gf and psychometric intelligence (IQ) on school performance, a second model was tested where school subjects were regressed separately on each of these two factors. Both effects were significant, but varied across subjects. The effects of gf on science, Greek, and mathematics were .87, .50, and .71, respectively. The corresponding effects of IQ were .41, .46, and .40, respectively.

Obviously, the constructs in our theory are strongly predictive of learning in three of the core subjects at both primary and secondary school. The differences between the two studies are interesting. Specifically, in the 8–11 years phase working memory is more highly related to school performance than gf. After the age of 12, it is G that is more highly related to school performance than WM. This pattern may suggest, on the one hand, that academically driven concepts in primary school are constructed anew. As a result, differences in representation- al capacity are reflected in learning differences in the construction of concepts. In secondary school, on the other hand, WM approaches ceiling but cognition still develops extensively. On the other hand, academic learning builds onto the concepts constructed in primary school. Thus, changes in cognition are better predictors of school learning than WM. It is also notable that psychometric and gf contribute independently to school learning. This indicates that school learning involves a developmental dimension, captured here by our cognitive development tasks, and an individual difference dimension, captured by psychometric intelligence. Interestingly, learning in language reflected individual differences in verbal intelligence as well.

4. Hidden constructs

Pascual-Leone opened a discussion that was never exhaustively undertaken in psychology: How we move from empirical constructs directly reflecting a particular type of measures (e.g., speed of processing, reflecting reaction times to speeded tasks; WM, reflecting storage and recall of information on WM tasks; and gf, reflecting the positive manifold of performance on reasoning or problem solving tasks) to hidden constructs reflecting underlying interactive processes that cannot be captured by any of the tasks used to measure empirical

Fig. 3. Relations between cognitive processes and school performance in science, Greek, and mathematics in primary (first number in each pair, $x^2(142) = 208.49$, CFI = .97, RMSEA = .06) and secondary school (second number, $x^2(162) = 347.44$, CFI = 1.0, RMSEA = .09). Note 1: Significant relations in bold. Note 2: Speed-school performance relations are indirect.

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constructs. Hidden constructs are no less real than empirical constructs. However, they operate on a different—non observable—level. They can in principle be uncovered and empirically measured if their distinct effect on already known empirical constructs is understood and operationalized. Examples in physics are Einstein’s relativity or the Higgs field, which capture the interactions underlying the relations between empirical constructs (such as spacetime and gravity in relativity and mass and energy in the Higgs field). In biology, DNA captures the interactions between evolution operating on macro-time, organization of proteins operating over an organism’s life-time, and phenotype. The distinctive effects of these constructs eventually become measurable when it is understood how they influence each of the empirical constructs and their interactions.

Blatant positivism hindered psychology to develop hidden constructs of this nature. They are needed, however, for paradigm shifts that would uncover laws of mind underlying our empirical and meta-empirical constructs. Pascual-Leone is right in pointing out that our Abstraction-Alignment-Cognizance (AACog) mechanism is one such construct. However, Pascual-Leone’s interpretation of the three functions, as stated in his commentary, deviates somewhat from our intended interpretation. In our model, abstraction does not necessarily involve reflection. Abstraction is a probabilistic inference mechanism sampling over statistical regularities in the environment (e.g., a property present in different objects and recurring sequences) and it operates in infancy, much earlier than reflection (Tenenbaum et al., 2011). Alignment is a relational mechanism that maps representations onto each other according to current understanding needs; similarity and semantic relevance provide direction and criteria for alignment (Demetriou et al., 2013). Cognizance is awareness and metarepresentation of mental content or processes. Metarepresentation is the encoding of similarities between representations into new representations (Demetriou & Kazi, 2006; Demetriou et al., 2011). One example drawn from Piaget would be the very moment a child discovers that different action sequences of counting the same set of pebbles always give the same number, having an insight into the conservation of number. Therefore, AACog is a hidden construct integrating empirical constructs such as inductive (abstraction) and analogical reasoning (alignment) and awareness about them (cognizance) (Demetriou & Kazi, 2006).

AACog-environment interactions cause representational and inferential change. We suggested that this occurs in four major developmental periods with two phases in each. The production of a new kind of representation dominates in the first phase of each period (i.e., pre-representations, representational blocks (Re), generic concepts (Conce), and general principles (P) from 0 to 1, 2 to 4, 6 to 8, and from 11 to 13 years, respectively). The alignment of mental units in each period dominates in the second phase (i.e., pre-representational, representational, conceptual, and principle alignments at 1–2, 4–6, 8–11, and 13–16 years, respectively). Therefore, in each period, representations proliferate in the first phase and they are mapped onto each other in the second phase, laying the ground for the generation of the new mental units of the following period. In short, development advances along a reconceptualization path, evolving from pre-representations to representations to concepts to principles: the ReConceP sequence (Demetriou et al., submitted).

AACog in each period generates insight into the period’s dominant mental constructs. That is, infants in the preRe period acquire an agential insight, when they realize that their actions change objects. Toddlers in the representational period acquire a representational insight (iRe). They understand that they possess representations that they can access to communicate with others and solve problems as the need arises. Primary school children in the conceptual period acquire an inferential insight (iIn). They understand that they think about representations and their stream of thought constrains their conclusions or solutions. Adolescents in the principle period acquire a formal insight (iForm) that gives them access to the formal relations between principles. Once available, mental insight displaces processing from representations themselves to the underlying mental processes connecting them; these will be woven into the representations of the next period. Thus, iReInForm captures the intentional constructive aspect of intellectual development and it reflects how cognizance operates in successive phases of development.

Speed, variability, and working memory index rather than cause variations between developmental phases or individuals in functional (speed, variability) or representational possibilities (WM). Intellectual development occurs at several levels and its form and rate of change vary depending upon the level concerned. ReConceP changes continuously (Fig. 4 in the target article) because new representations emerge from the alignment of existent representations. Thus, the likelihood of performing at the level of a given ReConceP phase increases as one comes closer to it, it is high at the end of the alignment phase, and it decreases with increasing distance from this phase. However, change in indicators of mental functioning varies, indicating discontinuity at some phases and continuity at others. Specifically, change in speed and variability accelerates with shifts to a new mental unit (Re → Conce → Re at 2, 6, and 11 years, respectively), suggesting that enhanced coherence coming with these shifts improves attention focusing and stimulus selection and identification, which determine the performance on speeded tasks (Demetriou et al., 2002). Changes in WM accelerate when the new units are in place and they are aligned, reflecting representational constructions of increasing complexity.

This discussion opens a number of important questions. For example, the developmental patterns above hint to Bruner (1966) view of cognitive development as a succession of symbolic modes (enactive → iconic → symbolic). Research must examine how possible shifts in symbolic modes relate to ReConceP shifts and how this is reflected in WM handling. We suggested here that these transitions change the mental units themselves that are represented and processed. To avoid misunderstanding, we coin several new terms to denote the mental unit dominating at each of the four periods: Percactons (perceptual and action complexes) in prerepresentations, pictons (ensembles of visual representations) in the representational period, concits (conceptual relations) in the conceptual period, and logions (explicit logical rules) in the principles period. These units have specific functional and representational requirements. It is notable, for instance, that visual working memory predicted change in gf from 4 to 7 years. However, from 8 years onwards verbal working memory kicks in as predictor of gf change, making concits and logions possible. Moreover, change in mental units may justify the
inference-WM entanglement observed, at each of these periods (Demetriou et al., 2013). In turn, these entanglements are reflected in the patterns of change observed in speed and variability. For example, searching in the space of concits is faster than searching in the space of pictons. Thus, the shift from pictons to concits is reflected in the drastic drop we observed in speed and variability in the Re → Conce transition. However, both concits and logions are both based on verbal WM. Thus, the shift from concits to logions does not change the search demands in the mental space for logions, which is consistent with the finding that there is no change in speed or variability at the Conce → P transition.

ReConceP-iReInForm speaks about how individuals may deal with novelty, which is of primary concern to psychometric theories. Progress on it makes problem solving more analytic and flexible, more inclusive in the consideration of alternatives, and more powerful in evaluating the truth and validity. Thus, more accurate and better organized concepts may be formed, better decisions made, and novelty successfully faced. Future research would have to examine how these sequences relate to standard expressions of intelligence, such as mental age and IQ.

5. Conclusion

Based on our constructive commentators, we expanded the findings and theory presented in the target article. Specifically, we showed, in agreement with Coyle, that variability is a distinct factor of processing efficiency. Moreover, we showed that variability is differentially related to WM and gf and also to developmental phase. With speed, it is an index of period transitions, and it wanes after adolescence, when processing cohesion peaks. In Pascual-Leone’s terms (Pascual-Leone, 1979), speed and variability together may indicate the mental energy available at a given developmental time. WM may be an index of efficiency in the environment-provoked investments of this energy in learning new concepts.

In agreement with Kail, we showed that developmental intelligence and psychometric intelligence are highly related but distinct. They are both needed to account for school performance and their role varies with developmental phase. Finally, in agreement with Pascual-Leone, we proposed a number of higher level hidden constructs which account for the data patterns observed between empirical constructs, such as speed, variability, WM, and reasoning or gf. Obviously, both patterns of relations and constructs need to be verified and extended by future research if we are to satisfactorily understand the human mind and strengthen its possibilities in education.

References