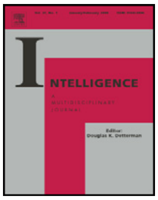
Intelligence 49 (2015) 94–109

Contents lists available at ScienceDirect

Intelligence



# Changing expressions of general intelligence in development: A 2-wave longitudinal study from 7 to 18 years of age

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## ARTICLE INFO

*Article history:*
Received 6 October 2014
Received in revised form 12 January 2015
Accepted 12 January 2015
Available online 28 January 2015

*Keywords:*
Attention control
Intelligence
Intellectual development
Processing speed
Working memory

## ABSTRACT

We present a study which investigated the inter-relations between processing speed, attention control, working memory, fluid intelligence, and mathematical reasoning from 7 to 18 years of age. To fulfil this aim, 478 participants drawn from each of the age years 7-17 years at first testing were examined twice, separated by a 12-month interval. Several simple reaction time, divided attention, and selective attention tasks examined processing efficiency. Forward and backward digit span tasks addressed working memory. Raven's standard progressive matrices addressed fluid intelligence and a task battery addressed to mathematical reasoning addressed its investment into a demanding cognitive domain. Relations between processes were explored by several types of structural equation models applied in three age groups: 8-10, 11-13, and 14-18 years. A powerful common general factor underlying all processes at both testing waves in all three age phases was found. The relative weight of these processes in the formation of this grand G differed between phases, with working memory, attention control, and Gf dominating in the three phases, respectively. Cross-lagged modeling revealed three tiers of mental organization (processing, representational, and inferential efficiency) interlinked by a core control program. This core is transcribed into inferential and problem solving ensembles of increasing compositionality at successive developmental phases. 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. Inductive and deductive inference and problem solving in different domains, such as mathematics, are important mechanisms of information integration. They underlie psychometric fluid intelligence (Gf) (Carroll, 1993; Jensen, 1998; Spearman, 1927) 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 and reasoning reflect differences in various aspects of processing and representational efficiency, such as processing speed (Jensen, 1998) and working memory capacity (WMC), respectively (Case, 1985; Cowan, Morey, Chen, & Bunting, 2007; Demetriou, Christou, Spanoudis, & Platsidou, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990). In their developmental version, several theories assume that changes in efficiency reflect changes in executive control. These are assumed to enable individuals to better attend to relevant information and

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http://dx.doi.org/10.1016/j.intell.2015.01.004
0160-2896/

handle it in working memory and inference (Case, 1985; Diamond, 2013; Zelazo et al., 2003).

However, the exact role of each of these factors is still debated. Some researchers emphasize speed as a purer index of the quality of information processing in the brain (e.g., Coyle, Pillow, Snyder, & Kochunov, 2011; Jensen, 1998, 2006). Others emphasize working memory capacity because it is the workspace of thinking (Kyllonen & Christal, 1990). Others emphasize executive control of attention, which allows self-directed deployment of information selection, processing, decision making, and action. In their view, executive control of attention is common to all, speed, WM, and Gf, explaining their relations (Cowan et al., 2007; Engle et al., 1999; Stankov & Roberts, 1997). Finally, others assume a causal linear relation between them such that changes in speed cause changes (or differences) in control of attention which enhance working memory which, in turn, cause changes (or differences) in Gf (Case, 1985; Coyle et al., 2011; Kail, 1991; Kail & Ferrer, 2007; Nettelbeck & Burns, 2010).

It is commonly accepted that from childhood to early adulthood, speed increases (Kail, 1991, 2007; Kail & Ferrer, 2007), attention becomes more focused, flexible, and selective (Brydges, Fox, Reid, & Anderson, 2014; Diamond, 2013; Pascual-Leone & Johnson, 2011), working memory capacity expands (Case, 1985; Halford et al., 1998; Pascual-Leone, 1970), and Gf can deal with concepts and problems of increasing complexity (e.g., Halford et al., 1998; Piaget, 1970). Demetriou et al. (2013), Demetriou, Spanoudis, Shayer, van der Ven, Brydges, et al. (2014)) showed recently that the relations between these constructs are more complicated than originally assumed. Specifically, they suggested that a common core of processes underlying Gf is always present in intellectual functioning. However, this core is systematically transformed in development. It changes in the kind of representations that it can handle at successive developmenal cycles (e.g., visual → verbal → abstract representations in the three last cycles respectively), the relations that it can build between representations, and the awareness about them. As a result, its relations to measures of processing and representational efficiency, such as speed and WMC, vary in development as a function of its current state.

The developmental version of Gf involves three fundamental processes which are always present in inference and problem solving: Abstraction, alignment, and cognizance (AACog). Abstraction spots or induces similarities between patterns of information, using mechanisms that may vary in development, such as perceptually based induction in infancy and deduction later on. Alignment is a relational mechanism that maps representations onto each other, enabling comparisons driven by current understanding or learning goals. Cognizance is awareness of the objects of cognition, cognitive processes, and cognitive goals. Executive control is a special expression of cognizance in that it reflects the self-regulation possibilities allowed by cognizance. Conceptual development is self-propelled because AACog continuously generates new mental content expressed in representations of increasing inclusiveness and resolution (Demetriou, Spanoudis, & Shayer, 2014).

AACog evolves through four major developmental cycles, with two phases in each. New representations emerge early in each cycle and their alignment dominates later. Each cycle culminates into insight about the cycle's representations and underlying inferential processes that is expressed into executive programs of increasing flexibility. These programs activate transition to the next cycle. In succession, the four cycles operate with episodic representations (birth to 2 years), mental representations (2-6 years), rule-based concepts (6-10 years), and principle-based concepts (11-18 years). Transitions within cycles occur at 4 years, 8 years, and 14 years, when relations between the representational units constructed earlier are worked out (Spanoudis, Demetriou, Kazi, Giorgalla, & Zenonos, 2015). It is notable that, despite differences in descriptions and interpretations, these cycles have been identified by all students of intellectual development (e.g., Case, 1985; Fischer, 1980; Pascual-Leone, 1970; Piaget, 1970). This convergence indicates a strong developmental phenomenon that needs to be understood.

In this paper we focus on the two cycles attained after the age of 6 years as this study is concerned only with them. In the first phase of the rule-based concepts cycle, at 6-8 years, there is a shift from "realistic" representations that are visible to the "mind's eye" to the inferential threads inter-linking them. At the beginning these function as semantic blocks defining generic concepts, such as object classes, number, causal attributions, etc. The integration of various conceptual spaces related to number, such as object arrays, number words, counting, digits, etc., into a common mental number line is a good example of an underlying mental construct in the domain of quantitative reasoning. In the next phase, the rules defining semantic blocks can systematically be aligned with each other, allowing grasping how two or more dimensions intersect with each other defining new forms of objects. Early in the next cycle, at 11-13 years, children grasp relations between rules and encode them as such. Thus, conceptual spaces may be explored as such in reference to one (in the first phase) or more (in the second phase) alternative principles. Analogical and algebraic reasoning in adolescence reflect this possibility. The four levels will be instantiated in Method in reference to the various batteries used.

Demetriou et al. (2013), Demetriou, Spanoudis, & Shayer (2014), Demetriou, Spanoudis, Shayer, van der Ven, et al. (2014) showed that changes in Gf were predicted by speed at the first phase of each 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. At the beginning of cycles processing speed is a better index because thought in terms of the new mental units is automated and expands fast over different contents. Later in the cycle, when networks of relations between representations are worked out, WMC is a better index because alignment and inter-linking of representations both requires and facilitates WMC. However, speed and WMC index rather than cause transitions in reconceptualization. Executive control and associated awareness of mental processes also change. Spanoudis et al. (2015) found that awareness mediates between processing and representational efficiency and thought, reflecting shifts in the level of executive control that individuals may exercise.

This article aims to further explore the relations between the main constructs of interest from late childhood to late adolescence. Specifically, we focus on the last phase of the cycle