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Cognitive correlates of developing intelligence: The contribution of working memory, processing speed and attention☆

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ABSTRACT

The present study examined the relations of general, fluid and crystallized intelligence with three cognitive functions – speed of processing, attention and working memory (WM) – in 158 7- to 18-year-old children and adolescents. Multiple measures of each of these cognitive functions were obtained. Intelligence was assessed using the Wechsler Abbreviated Scale of Intelligence (WASI). Structural equation modeling was performed to determine which cognitive function served as the best predictor of intelligence. The results showed that only WM predicted general, fluid and crystallized intelligence when controlling for the other two cognitive functions. Neither processing speed nor attention significantly predicted intelligence. These findings indicate that WM is the main cognitive function underlying general, fluid and crystallized intelligence in children and adolescents. Moreover, results indicated that age-related changes in WM lead directly to developmental changes in intelligence (general, fluid and crystallized).

1. Approaching intelligence through elementary cognitive processes

The distinction between fluid and crystallized intelligence is important because it helps to explain how intellectual ability develops and interacts with fundamental cognitive processes like memory and attention (Cattell, 1963, 1971; Horn & Cattell, 1966). Fluid intelligence reflects the ability to reason abstractly in novel situations and it is considered to be biologically marked. Tests of fluid intelligence include matrices, analogies, series completion and other tasks requiring inductive reasoning. Crystallized intelligence represents the skills and knowledge acquired through experience, education and acculturation. It is measured by tests examining vocabulary, general knowledge, and verbal comprehension.

The investigation of the cognitive underpinnings of human intelligence is of particular interest in intelligence research. In the search for the cognitive correlates of intelligence, investigators attempted to reveal the cognitive functions that predict psychometric test scores (Deary, 2012; Deary & Caryl, 1997; Fink & Neubauer, 2005; Friedman et al., 2006; Tillman, Bohlin, Sorensen, & Lundervold, 2009). In this approach, elementary cognitive tasks standing for specific cognitive processes are used to predict individual differences in intelligence test scores (Deary & Caryl, 1997).

This research showed that speed of processing, attention control, and working memory (WM) are important cognitive correlates of intelligence (Burns, Nettelbeck, & McPherson, 2009; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Deary, 2012; Deary & Caryl, 1997; Fink & Neubauer, 2005; Friedman et al., 2006; Schweizer, 2005; Schweizer & Moosbrugger, 2004; Schweizer, Moosbrugger, & Goldhammer, 2005; Tillman et al., 2009). These three cognitive functions are thought to be the major cognitive pillars of intelligence.

Speed is thought to reflect the overall efficiency of the brain to register and process information (Deary, 2001, 2012; Jensen, 2006; Schweizer, 2005). Two types of tasks are used in this research, inspection time and reaction time tasks (Deary, 2001). Performance on inspection time tasks under nontime constraints significantly correlates with intelligence (Deary, 2001, 2012; Grudnik & Kranzler, 2001; Jensen, 2006; Luciano et al., 2005; Schweizer, 2005; Sheppard & Vernon, 2008). Inspection time correlates higher with fluid intelligence, but it also correlates with crystallized intelligence (Luciano et al., 2005; Sheppard & Vernon, 2008). However, it is worth noting that studies on adults (Conway et al., 2002; Fry & Hale, 1996; Nettelbeck & Burns, 2010) and children (Fry & Hale, 1996; Kail, 2007; Nettelbeck & Burns, 2010) showed that speed does not have a significant direct effect on intelligence when controlling for WM. This finding concerns only fluid intelligence since these studies focused on this type of intelligence.

WM refers to a system of limited capacity which is responsible for maintaining information for short periods of time while simultaneously

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manipulating this information by specific mental operations (Baddeley & Hitch, 1974; Cowan, 1998). Therefore, WM consists of two structural components: (a) a short-term storage that stores information over a brief period of time, and (b) a processing component that processes the target information; it is generally referred to as the executive or control component of WM (Conway et al., 2002; Conway, Kane, & Engle, 2003; Engel de Abreu, Conway, & Gathercole, 2010; Engle, Tuholski, Laughlin, & Conway, 1999; Engle & Kane, 2004). WM is measured by complex memory span tasks which involve both a short-term storage requirement and a concurrent processing requirement. WM has been systematically found to relate to both fluid and crystallized intelligence in both adults (Ackerman, Beier, & Boyle, 2005; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Colom, Abad, Rebollo, & Shih, 2005; Colom, Rebollo, Abad, & Shih, 2006; Conway et al., 2002; Engle et al., 1999; Friedman et al., 2006; Schweizer & Moosbrugger, 2004) and children (Engel de Abreu et al., 2010; Hornung, Brunner, Reuter, & Martin, 2011; Tillman et al., 2009; Tillman, Nyberg, & Bohlin, 2008).

A major disagreement about WM–intelligence relations was concerned with the component causing individual differences in fluid and crystallized intelligence. Some researchers claimed that short-term storage is the liaison between WM and intelligence (Colom et al., 2008; Colom, Flores-Mendoza, Quiroga, & Privado, 2005; Colom et al., 2006). Others argued that the processing/executive component of WM is responsible for this relation (Conway et al., 2002; Conway et al., 2003; Engle et al., 1999; Heitz, Unsworth, & Engle, 2005; Kane et al., 2004). Research exploring the WM–intelligence relations in children is also inconclusive. In line with Colom and colleagues, Hornung et al. (2011) found that the short-term storage component underlies primarily the relation between WM and fluid intelligence in young children. In contrast, Engel de Abreu et al. (2010) found that the executive component of WM accounts for this relation. Other studies suggest that both components of WM are important (Tillman et al., 2009; Tillman et al., 2008).

Some investigators emphasized the role of attention (control of processing) (Burns et al., 2009; Heitz et al., 2005; Schweizer & Moosbrugger, 2004; Schweizer et al., 2005; Tillman et al., 2009). Heitz et al. (2005) showed that the ability to control attention is closely related to fluid intelligence. Schweizer et al. (2005) examined the relation between fluid intelligence and different types of attention in adults, including interference, inhibition, sustained attention, alertness and attentional switching. They found that each type of attention was related to fluid intelligence. They suggested that attention may be a cognitive source of intelligence, among other sources. However, some studies provided evidence to the contrary. According to Schweizer and Moosbrugger (2004) this is due to the fact that there are different types of attention which are independent of each other, and they differentially relate to intelligence.

Attention is closely associated to executive functions. Executive functions involve different cognitive operations which are associated with goal-directed behavior (Miller & Cohen, 2001). These include inhibition of prepotent responses, interference control, shifting between tasks or mental sets, planning, etc. WM is considered to be a good example of executive functions. Therefore, executive functions is a general concept encompassing both WM and different types of attention. WM and attention are very closely related constructs. Heitz et al. (2005) suggested that the executive component of WM is an attentional construct which preserves relevant information in an active state in the presence of interference. Several studies revealed moderate to strong relations between WM and different types of attention in both adults (Burns et al., 2009; Friedman et al., 2006; Miyake et al., 2000; Schweizer & Moosbrugger, 2004) and children (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Wu et al., 2011).

Studies examining the relations between several executive functions and intelligence indicated that not all of them are related to intelligence. Friedman et al. (2006) examined updating in WM, inhibiting prepotent responses, and shifting between mental sets. They found that updating equally predicted both fluid and crystallized intelligence in adults, whereas inhibiting and shifting did not predict either of them. Brydges, Reid, Fox, and Anderson (2012) replicated Friedman et al. (2006) study. In contrast to the study of Friedman et al. (2006), they found a single factor of executive functions underlying WM, inhibition, and shifting in children. This factor strongly predicted both fluid and crystallized intelligence equally. There is also research indicating varying relations between different aspects of attention and different facets of intelligence. For example, Tillman et al. (2009) found that interference control did relate to fluid intelligence, but not to crystallized intelligence in children. In the same study sustained attention had a significant contribution to crystallized intelligence, but not to fluid intelligence. On the contrary, Schweizer and Moosbrugger (2004) found that after controlling for WM, sustained attention had a significant contribution to fluid intelligence in adults.

To identify the cognitive correlates of intelligence requires concurrent assessment of all predictors in order to dissociate their individual contributions. The present study comprises a comprehensive and concurrent assessment of all the above constructs in an attempt to investigate the cognitive underpinnings of intelligence, examining the contribution of speed of processing, attention, and WM to the prediction of general, fluid, and crystallized intelligence in a sample of 7- to 18-year-old children and adolescents. Childhood and adolescence are periods when processing speed, WM, attention, fluid and crystallized intelligence all improve extensively. Developmental research indicated that increases in processing speed and WM during childhood and adolescence lead to increases in fluid intelligence (Fry & Hale, 1996; Kail, 2007; Nettelbeck & Burns, 2010). Here we investigated whether developmental changes in each of the above three cognitive functions lead directly to developmental increases in three aspects of intelligence, general, fluid, and crystallized.

The following predictions will be tested. Firstly, it was hypothesized that, controlling for the other correlates of intelligence included in the models (namely, processing speed, attention and age), WM would have a significant direct effect on general intelligence, but also on each of its dimensions, fluid and crystallized intelligence. The significant substantial relationship between WM and intelligence is a robust finding in the literature on the cognitive correlates of intelligence (Burns et al., 2009; Colom et al., 2008; Conway et al., 2002; Deary, 2012; Friedman et al., 2006; Schweizer, 2005; Schweizer & Moosbrugger, 2004; Tillman et al., 2009).

Second, although there is ample evidence demonstrating a significant relation between processing speed and intelligence, we hypothesized that, when controlling for the other correlates of intelligence included in the models (namely, WM, attention, and age), processing speed would not have a significant direct effect on intelligence (general, fluid and crystallized intelligence). This prediction was based on some previous studies on fluid intelligence which assessed both speed of processing and WM and found that, when controlling for WM, processing speed did not have a significant direct effect on fluid intelligence (Conway et al., 2002; Fry & Hale, 1996; Kail, 2007; Nettelbeck & Burns, 2010). We predicted that this finding would also hold for both general and crystallized intelligence.

Third, due to the inconsistency of findings of previous research regarding the relationship between attention and intelligence (Friedman et al., 2006; Schweizer & Moosbrugger, 2004; Schweizer, 2005; Tillman et al., 2009), we have chosen to leave open the prediction regarding the contribution of attention to intelligence, when controlling for the other predictors of intelligence included in the models (WM, processing speed and age).

Fourth, we have also chosen to leave open the prediction concerning the direct effect of age on fluid intelligence, when controlling for the three cognitive functions (processing speed, attention, WM), since previous studies in the developmental context yielded contradictory findings. For example, Fry and Hale (1996) found that controlling for processing speed and WM, age had a significant direct effect on fluid