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Children's working memory: Its structure and relationship to fluid intelligence

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ABSTRACT

Working memory (WM) has been predominantly studied in adults. The insights provided by these studies have led to the development of competing theories on the structure of WM and conflicting conclusions on how strongly WM components are related to higher order thinking skills such as fluid intelligence. However, it remains unclear whether and to what extent the theories and findings derived from adult data generalize to children. The purpose of the present study is therefore to investigate children's WM ($N = 161$), who attended classes at the end of kindergarten in Luxembourg. Specifically, we examine different structural models of WM and how its components, as defined in these models, are related to fluid intelligence. Our results indicate that short-term storage capacity primarily explains the relationship between WM and fluid intelligence. Based on these observations we discuss the theoretical and methodological issues that arise when children's WM is investigated.

Working memory (WM) is an essential cognitive function in everyday life: it enables people to store and process important information, to inhibit irrelevant information, and to take the necessary incremental steps to achieve goals. This holds for people of all ages. It therefore comes as no surprise that WM has emerged to be strongly related to fluid intelligence (GF) in adult samples (Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Colom, Abad, Rebollo, & Shih, 2005; Colom, Rebollo, Abad, & Shih, 2006; Colom, Shih, Flores-Mendoza, & Quiroga, 2006; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Conway, Kane, & Engle, 2003; Engle, Tuholski, Laughlin, & Conway, 1999; Kane & Engle, 2002; Krumm et al., 2009; Oberauer, Süß, Wilhelm, & Wittmann, 2008). Although WM is critical for successful complex cognitive functioning across the lifespan, most previous studies in this research field have focused on adult samples and considerably less research attention has been paid to WM in children. Despite the general consensus that WM capacities develop significantly during childhood (Cowan et al., 2005; Engel de Abreu, Conway, & Gathercole, 2010; Gathercole, 1999), surprisingly little is known about whether and to what extent theories and empirical findings on WM derived from adult data generalize to children. Drawing on key theories and findings on WM and data obtained from 5-to-7-year-old children, this article therefore rigorously investigates (1) the structure of WM and (2) the relationship between WM components and fluid intelligence in children.

1. The structure of WM components

1.1. Definitions and measurement

Working memory (WM) refers to a complex cognitive system of limited capacity that stores information while simultaneously processing the same or additional information (Baddeley & Hitch, 1974; Cowan, 1999; Tuholski, Engle, & Baylis, 2001). Two essential structural components of WM are therefore (a) a *short-term storage component* (i.e., short-term memory, STM) that holds information briefly, and (b) a *non-storage component* responsible for further processing, generally

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referring to executive attention control (Conway et al., 2003). Short-term storage capacity is limited to about 3–5 chunks of information in adults and to about 3 chunks of information in children (Ricker, AuBuchon, & Cowan, 2010). To overcome this capacity limit, additional processes, such as executive attention control, are therefore required to store larger amounts of information, to combat interference and decay (Cowan, 2008; Engle et al., 1999).

While STM is usually measured by simple span tasks that require the storage and direct recall of information, WM is usually measured by complex span tasks that require the simultaneous storage and additional processing of information (in terms of a secondary processing component) (Conway et al., 2003; Gathercole, 1999). Higher scores on simple spans are indicative of higher STM capacity, while higher scores on complex spans are indicative of higher WM capacity (i.e., executive attention control) (Engle et al., 1999). Even though, STM and WM refer to theoretically distinct concepts, usually assessed separately, both concepts are measured by tasks that tap short-term storage, and non-storage processes such as executive attention control and domain-specific skills and strategies to some extent (Conway et al., 2003; Engle et al., 1999). Thus, the distinction between STM and WM seems ambiguous and it might primarily translate the degree to which storage and non-storage processes are implicated in the tasks assessing both concepts. The next section therefore draws on different conceptualizations of WM and recent research findings to develop different structural models of WM. These structural models make different assumptions about how children's individual differences on these tasks can be explained.

1.2. Structural models of WM for children

In this section we have identified 6 different models for WM in children. *Model 1* tests the hypothesis of a unitary WM component that is that STM and WM are indistinguishable in early childhood (potentially becoming increasingly differentiated with age). Recent empirical findings indicate that WM and STM measures might reflect the same latent construct (Colom, Rebollo, et al., 2006; Colom, Shih, et al., 2006; Kyllonen & Christal, 1990; Unsworth & Engle, 2006, 2007). For example, Unsworth and Engle (2007) suggest that simple and complex span tasks assess the same basic cognitive processes (active maintenance through primary memory and retrieval through secondary memory) and, as a matter of parsimony, conclude that STM and WM are indistinguishable.

Model 2 tests the opposing theoretical position that STM and WM are distinct constructs. Shah and Miyake (1996) suggested that simple span tasks involve short-term storage processes, whereas complex span tasks involve both storage *and* executive attention control processes. An important observation in previous studies of WM is that adults' individual performances on tasks measuring WM and STM differ considerably, which further underscore their distinction (Ackerman, Beier, & Boyle, 2005; Engle et al., 1999). Engel de Abreu et al. (2010) found distinct STM and WM components in 5-to-9-year-old children. Likewise, Gathercole and Pickering (2000) found separate systems for executive and verbal storage processes in 6- and 7-year-old children.

Model 3 investigates two domain-specific WM components for verbal and visuo-spatial information respectively (Park et al., 2002). Verbal and visuo-spatial storage processes are viewed as separate developing components in WM that rely on distinct neural substrates (Becker, MacAndrew, & Fiez, 1999; Gathercole, 1998; Gathercole, Pickering, Ambridge, & Wearing, 2004; Pickering, Gathercole, & Peaker, 1998; Smith & Jonides, 1997). Previous findings indicate distinct verbal and visuo-spatial components of STM and WM in 4-to-13-year-old children (Alloway, Gathercole, & Pickering, 2006; Tillman, Nyberg, & Bohlin, 2008).

Model 4 investigates the standard WM model (Baddeley & Hitch, 1974) that comprises a *central executive* and two domain-specific storage systems—the *phonological loop* and *the visuo-spatial sketchpad*—representing either verbal or visuo-spatial STM (Awh et al., 1996). Importantly, in this model, storage refers to an attention-free function. A study with 6-year-old children (Gathercole et al., 2004) and even younger children supported this WM model (Alloway, Gathercole, Willis, & Adams, 2004).

Model 5 tests Cowan's (1995, 1999, 2001) WM framework, according to which WM capacity refers to a core storage capacity. While in Model 4 storage is interpreted as an attention-free function, Model 5 suggests that storage may draw on attention. Here, short-term storage capacity reflects the focus or scope of attention. More specifically, a task at hand might activate a vast bank of long-term memory representations. Attention is needed to focus on the relevant information in order to store it. Thus, variance in memory tasks can be explained by a core storage capacity and further specific processes engaged in the task. To reflect these ideas, Model 5 defines a domain-general component (*COMMON*) that affects all memory span tasks and that is interpreted as short-term storage (see Colom, Rebollo, et al., 2006; Colom, Shih, et al., 2006; Engle et al., 1999). Furthermore, the model includes two domain-specific components (*verbal specific* and *visuo-spatial specific*) that affect either verbal or visuo-spatial span tasks. Both specific components are interpreted as task-relevant and domain-specific processes reflecting specific activations of either language-based or visual-based networks (D'Esposito, 2007; Zimmer, Münzer, & Umla-Runge, 2010). They may also represent long-term memory representations (e.g., specific skills and strategies) activated by the task at hand (Cowan, 1995, 2001, 2008; Cowan et al., 2005).

Model 6 capitalizes on recent structural conceptions of WM in adults (Unsworth & Engle, 2007) and attempts to separate storage from executive attention control processes. More specifically, Model 6 comprises a common short-term storage factor (*STM common*) that affects all verbal span tasks, and a *WM residual* factor that represents executive processes that are needed in addition to STM processes to complete complex span tasks (Engle et al., 1999). Model 6 further includes a general visuo-spatial WM factor (*VSWM*) that affects simple visuo-spatial span tasks (cf. Gathercole & Pickering, 2000).

Overall, the components in Models 5 and 6 are more process-based and seem to be easier to interpret than the components in the modular WM model (cf. Model 4) that have been applied in most previous research in developmental and educational psychology. Furthermore, Models 5 and 6 align well with recently tested structural models of WM in