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## The structure of working memory in young children and its relation to intelligence

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## ABSTRACT

This study investigated the structure of working memory in young school-age children by testing the fit of three competing theoretical models using a wide variety of tasks. The best fitting models were then used to assess the relationship between working memory and nonverbal measures of fluid reasoning (*Gf*) and visual processing (*Gv*) intelligence. One hundred sixty-eight English-speaking 7–9 year olds with typical development, from three states, participated. Results showed that Cowan's three-factor embedded processes model fit the data slightly better than Baddeley and Hitch's (1974) three-factor model (specified according to Baddeley, 1986) and decisively better than Baddeley's (2000) four-factor model that included an episodic buffer. The focus of attention factor in Cowan's model was a significant predictor of *Gf* and *Gv*. The results suggest that the focus of attention, rather than storage, drives the relationship between working memory, *Gf*, and *Gv* in young school-age children. Our results do not rule out the Baddeley and Hitch model, but they place constraints on both it and Cowan's model. A common attentional component is needed for feature binding, running digit span, and visual short-term memory tasks; phonological storage is separate, as is a component of central executive processing involved in task manipulation. The results contribute to a zeitgeist in which working memory models are coming together on common ground (cf. Cowan, Sauls, & Blume, 2014; Hu, Allen, Baddeley, & Hitch, 2016).

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## Introduction

Working memory is the portion of our human memory system responsible for simultaneously processing and storing incoming information. There are a number of prominent theories of working memory that differ

primarily on whether working memory can be divided into domain-specific components, with unique processing and short-term storage capabilities (e.g., Alloway, Gathercole, & Pickering, 2006; Baddeley, 2000; Baddeley & Hitch, 1974; Shah & Miyake, 1996), or whether working memory is part of a larger, more unitary construct primarily guided by the focus of attention (e.g., Cowan, 2001; Engle, 2002). Intelligence encompasses an individual's ability to learn, reason, adapt, understand, and overcome obstacles by thinking. Nonverbal intelligence measures assess these abilities using items that do not require overt language, and thus reduce the impact of language ability on perfor-

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mance. In this study we compared the statistical fit of four competing working memory models in children, including a new hybrid model, and then assessed the relationship between our best-fitting working memory models and nonverbal measures of fluid reasoning and visual processing intelligence.

There is an increased interest in the structure of working memory in children because of the central role working memory plays in learning (Alloway, 2009; Alloway, Gathercole, Kirkwood, & Elliott, 2009). In the last decade alone, working memory has been investigated in children with intellectual disability (Van der Molen, 2010; Van der Molen, Henry, & Van Luit, 2014), poor reading comprehension (Carretti, Cornoldi, De Beni, & Romanò, 2005), dyslexia (Jeffries & Everatt, 2004), language impairment (Gray, 2006; Leonard et al., 2007; Montgomery & Evans, 2009), autism (Gabig, 2008), attention deficit hyperactivity disorder (Alloway & Cockcroft, 2014), and fetal alcohol syndrome (Paolozza et al., 2014), as well as in children who are learning two or more languages (Blom, Kuntay, Messer, Verhagen, & Leseman, 2014; Morales, Calvo, & Bialystok, 2013). Because working memory is so integral to learning, it is important to determine its structure early in the elementary school years when assessment information can help lead to treatments to prevent future learning problems (Nevo & Breznitz, 2013) and when children are mature enough to complete the wide variety of experimental tasks that permit a full and fair test of working memory structure.

There is also an increased interest in the relationship between working memory and intelligence in children because different components of working memory are thought to predict different aspects of intelligence (Mackintosh & Bennett, 2003) and because some have proposed that working memory actually accounts for individual differences in fluid intelligence, which is the ability to adapt thinking to solve new problems (Conway, Cowan, Bunting, Theriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Oberauer, Schultze, Wilhelm, & Suß, 2005; but see Gignac & Watkins, 2015).

#### *The structure of working memory in children*

A number of studies have investigated the structure of working memory in children. As shown in Table 1, seven of eight structural studies have considerable overlap in tasks. Although there were differences in the age and primary language of participants, and to some extent how working memory was assessed, results for these modeling studies were quite similar. In general, there was evidence for separate central executive, phonological, and visuospatial type factors. The exception was the study of 8–9-year-old Portuguese children by Campos, Almeida, Ferreira, and Martinez (2013). The fit for their initial confirmatory factor model, with three latent factors (phonological loop, central executive, visuospatial sketchpad), was adequate; however, there was a high correlation (.91) between the central executive and the visuospatial sketchpad factors. They concluded that a model with executive functioning and visuospatial tasks on the same factor was most parsimonious, and therefore they suggested a new two-factor

structure as an alternative to the three-factor model. Consistent with this result, Michalczyk, Malstadt, Worgt, Konen, and Hasselhorn (2013) found that a three-factor model fit their data for each age group tested (5–6, 7–9, 10–12), but they reported a “remarkably high correlation between the visual-spatial sketchpad and the central executive” (.81) (p. 227), especially in the younger groups.

Of the studies in Table 1, the investigation by Hornung, Brunner, Reuter, and Martin (2011) is of particular interest because the authors pitted six competing working memory theories against each other in their study of 161 Luxembourgish or Portuguese speaking 5–7 year olds. Using two indicators for verbal simple span, two for verbal complex span, and two for visuo-spatial span, they tested (a) a unitary working memory model, (b) a two-factor model with distinct short-term memory and working memory components, (c) a two-factor model with distinct verbal and visuo-spatial working memory components, (d) a three-factor model (cf. Baddeley & Hitch, 1974) with central executive, phonological loop, and visuo-spatial sketchpad components, (e) a three-factor model (cf. Cowan, 1995a, 1999, 2001) with a domain-general short-term storage component reflecting the focus of attention and two domain-specific components reflecting verbal and visuospatial processes, and (f) a three-factor model based on adult research (cf. Unsworth & Engle, 2007) with a common short-term verbal storage component, a working memory residual component representing executive processes, and a general visuo-spatial storage component. The fit for the last three models was excellent and nearly identical, meaning that there was no clear winner. The authors acknowledged limitations in their study, including the need to administer a wider array of tasks. In particular, their battery did not include complex visuospatial tasks or tasks tapping executive function only.

Also missing from the Hornung et al. study, and from most studies of the structure of working memory in children, were tasks designed to assess episodic buffer function. Baddeley (2000) proposed that the episodic buffer is an independent working memory component with its own temporary storage capacity – a kind of ‘back-up store that is capable of supporting serial recall, and presumably of integrating phonological, visual, and possibly other types of information’ over space and time (p. 419). One study by Alloway, Gathercole, Willis, and Adams (2004) did assess episodic buffer function using two spoken sentence recall tasks. Their final model included episodic buffer, central executive, and phonological loop factors. However, they did not assess visuospatial function; thus, to our knowledge there is no structural test of Baddeley’s (2000) four-component working memory model in the research literature.

#### *Open questions about working-memory models*

The studies discussed above raise several important questions about models of working memory. First, can the statistical fit of working memory models proposed by Baddeley and Hitch (1974) versus Cowan (1995a, 1999, 2001) be differentiated, provided that a wider variety of indicators are included in the models? As shown in Table 1,

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