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Storage capacity explains fluid intelligence but executive control does not

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A B S T R A C T

We examined whether fluid intelligence (Gf) is better predicted by the storage capacity of active memory or by the effectiveness of executive control. In two psychometric studies, we measured storage capacity with three kinds of task which required the maintenance of a visual array, the monitoring of simple relations among perceptually available stimuli, or the quick update of information. Executive control was measured with tasks reflecting three executive functions, namely attention control, interference resolution, and response inhibition. Using structural equation modeling, we found that all storage tasks loaded on one latent variable, which predicted on average 70% of variance in Gf (Studies 1 and 2). On the contrary, neither interference resolution nor response inhibition was substantially related to Gf or to any other variable (Study 1). Although attention control predicted on average 25% of Gf variance (Studies 1 and 2), when storage capacity was statistically controlled for, attention control no longer significantly explained Gf.

1. Introduction

The last twenty years of research on individual differences in cognition have unquestionably enriched our understanding of fluid intelligence (Gf; also called fluid ability, fluid reasoning, or reasoning ability), one of the most important human abilities, which is closely related to general ability (*g* factor). Gf indicates how well (or how poorly) people reason and solve problems in novel, abstract tasks. The main observation shows that the capacity of working memory (WM), a cognitive mechanism responsible for active maintenance of information crucial for current processing, is the strongest predictor of Gf. Several studies (e.g., Ackerman, Beier, & Boyle, 2002, 2005; Colom, Abad, Rebollo, & Shih, 2005; Conway, Cowan, Bunting, Therriault, & Minkoff, 2003; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002) estimated that working memory capacity (WMC), a latent variable being measured with either so-called complex span tasks or batteries of diverse WM tasks, shares a huge amount of common variance with Gf. According to different sources, this amount can be 50% (Kane, Hambrick, & Conway, 2005), 72% (Oberauer, Schultze, Wilhelm, & Süß, 2005), and even 92% (Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004). However, *what* WM tasks really measure and *why* WM and Gf are so strongly related is very much disputed (e.g., Colom et al., 2005; Cowan, 2001; Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007; Oberauer, Süß, Wilhelm, & Sander, 2007; Unsworth & Spillers, 2010). Several theories proposed different cognitive mechanisms presumed to underlie common variation in working memory and Gf.

In the present paper, we focus on two influential groups of theories of such mechanisms. One group of theories suggest that individual performance in both WM tasks and Gf tests depends on the quality of control over some cognitive processes like directing attention or triggering responses (ability henceforth referred to as *executive control*). On the contrary, the other group of theories propose that the capacity (henceforth called *storage capacity*) to simultaneously maintain the maximum possible amount of information in some kind of active memory is crucial for both WM and Gf. The general aim of our research was to confront the predictions of both approaches by estimating in one structural equations model (SEM) the coefficients of paths leading from latent variables

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representing either executive control or storage capacity to the fluid ability.

1.1. Executive control theories of working memory and fluid intelligence

1.1.1. Attention control (goal maintenance)

The attention control (also named executive attention) theory proposed by Engle, Kane, and their collaborators (e.g., Engle & Kane, 2004; Kane et al., 2007) suggests that individual performance in both WM tasks and Gf tests depends on the quality of domain-general control over attention. According to these authors, both highly capacious WM and correct fluid reasoning rely on the effective focusing of attention on task-relevant information, and on the blocking of potential distraction. Subjects with low attention control capabilities suffer from poor maintenance of task goals and from frequent capture by irrelevant stimuli and/or processes.

Some indirect evidence for the executive-attention theory came from strong relationships between Gf and latent variables believed to represent executive control, which were calculated from complex span task scores (Conway et al., 2003; Engle et al., 1999; Kane et al., 2004). More direct evidence consisted of significant correlations between WMC and the indices of attention control derived from tasks more evidently requiring attention. Example indices are error rates in the antisaccade task (Unsworth, Schrock, & Engle, 2004), in the flanker task (Heitz & Engle, 2007), and in incongruent trials of the high-proportion-congruent version of the Stroop task (Kane & Engle, 2003). Other instances include lapses of attention in a psychomotor vigilance task (Unsworth, Redick, Lakey, & Young, 2010) and in dichotic listening task (Colflesh & Conway, 2007). These errors/lapses were shown to result from the loss of the task goal (e.g., "don't read the word but name its color" in the Stroop) from attentional focus, while this goal should be endogenously maintained and protected from some dominant process (i.e., reading a word). When stimuli themselves remind a subject what the task is and goal neglect is unlikely, as in the low-proportion-congruent Stroop, then low-WMC participants commit a similar number of errors as high-WMC ones do (Kane & Engle, 2003). Moreover, several studies have demonstrated significant (though usually moderate) correlations between error rates in attention-demanding tasks and Gf scores (e.g., Buehner, Krumm, & Pick, 2005; Schweizer, Moosbrugger, & Goldhammer, 2005; Unsworth et al., 2010; Unsworth & Spillers, 2010).

1.1.2. Interference resolution

However, Kane and Engle (2003) found that though low- and high-WMC participants do equally well in the low-proportion-congruent condition of the Stroop task, the former demonstrate increased interference effects, measured as a difference in mean latency between incongruent and neutral trials. Moreover, a time to initiate a correct antisaccade, one that must be based on a properly maintained task goal, was also found to significantly predict WMC (Unsworth et al., 2004). So, according to Engle and Kane (2004), the individual efficiency of interference resolution, described as a gating mechanism that prevents distracting stimulation from entering the central stages of cognition and activating improper processes (Wilson & Kipp, 1998), is a distinct control-related factor, which also limits both WMC and Gf.

Some studies have provided evidence on the significant (though usually weak) relation between Gf and latency effects in interference-rich paradigms, such as the Stroop (Dempster & Corkill, 1999), the Navon task (Nęcka, 1999), and the flankers (Unsworth & Spillers, 2010; Unsworth et al., 2010).

1.1.3. Inhibition

Another influential executive control theory, which has been proposed by Hasher, Zacks, and collaborators (Hasher, Lustig, & Zacks, 2007; Hasher & Zacks, 1988; Lustig, May, & Hasher, 2001), points out that inhibitory abilities are the primary determinants of WMC and many other cognitive abilities. Simply, "…what most WM span tasks measure is inhibitory control" (Hasher et al., 2007, p. 231). This stance was based on observations showing that a decrease in imposed interference, which needs to be inhibited, significantly helps aging people to deal with WM tasks (Lustig et al., 2001). It was expected that the same factor may also help low-WMC young adults (Hasher et al., 2007).

In explanations of the results regarding tests of executive control, like the antisaccade, Stroop, vigilance, and dichotic listening tasks, the inhibition theory is consistent with, and indiscriminable from, the attention control and interference resolution theories. According to the inhibition theory, what people scoring high on IQ tests do within tests of executive control is just better inhibition of prosaccades, word reading, ruminations, or irrelevant channel, respectively. However, as the theory pertains to the concept of inhibition in a general way, it must also predict correlations between WMC/Gf and tasks that directly require inhibition. One such established task is a go/no-go paradigm, which consists of a rapid presentation of stimuli and a need to withheld responses for some previously defined no-go stimuli, while quickly responding for the go stimuli. The inhibition theory (see Hasher et al., 2007) suggests that such a motor inhibition may often be depleted, for example during individually varied non-optimal time of day. However, a recent study by Redick, Calvo, Gay, and Engle (2011) showed no significant correlation between the number of correct no-go trials and WMC. In another go/no-go study (McVay & Kane, 2009), mixed results on inhibition-WMC link were observed, as significant correlations were found only for some versions of the task (for a discussion see Redick et al., 2011). Also, Friedman et al. (2006) found no significant correlation between another hallmark test of inhibition, a stop-signal task (Verbruggen & Logan, 2008), and two measures of Gf. So, predictions of the inhibition theory, which regard relation of response inhibition to WM and Gf, have not yet been convincingly corroborated.

1.2. Storage-capacity theories of working memory and fluid intelligence

1.2.1. Capacity as the maximum number of chunks held in working memory

Some influential models of WM assume that a WM structure responsible for holding the most activated and most easily accessible information, called — depending on the particular model — "primary memory" (Unsworth & Engle, 2007), "the focus of attention" (Cowan, 2001), "activation