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Involvement of Spearman's g in conceptualisation versus execution of complex tasks

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ABSTRACT

Strong correlations between measures of fluid intelligence (or Spearman's g) and working memory are widely reported in the literature, but there is considerable controversy concerning the nature of underlying mechanisms driving this relationship. In the four experiments presented here we consider the role of response conflict and task complexity in the context of real-time task execution demands (Experiments 1–3) and also address recent evidence that g confers an advantage at the level of task conceptualisation rather than (or in addition to) task execution (Experiment 4). We observed increased sensitivity of measured fluid intelligence to task performance in the presence (vs. the absence) of response conflict, and this relationship remained when task complexity was reduced. Performance-g correlations were also observed in the absence of response conflict, but only in the context of high task complexity. Further, we present evidence that differences in conceptualisation or 'modelling' of task instructions prior to execution had an important mediating effect on observed correlations, but only when the task encompassed a strong element of response inhibition. Our results suggest that individual differences in ability reflect, in large part, variability in the efficiency with which the relational complexity of task constraints are held in mind. It follows that fluid intelligence may support successful task execution through the construction of effective action plans via optimal allocation of limited resources.

1. Introduction

Strong correlations between performance on tests of working memory capacity (WMC) and fluid intelligence (g) are well established (e.g., Ackerman, Beier, & Boyle, 2002; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002; Unsworth, Redick, Lakey, & Young, 2010). The mediating factors in this relationship, however, are not fully understood. Traditionally, the working memory (WM) system has been presented as a mental workspace associated with the concurrent storage and processing of information; Baddeley and Hitch's (1974) multicomponent WM model, for example, comprises domain-specific storage buffers and a central executive. Complex span tests, which typically assess memory for words or digits in the face of a demanding interleaved task are among the best measures of WMC and are also sensitive to variations in fluid intelligence. In contrast, simple span tests, which do not encompass additional processing demands, are typically weakly correlated with measures of WMC and intelligence (e.g., Conway, Kane, & Engle, 2003; Daneman & Carpenter, 1980; Engle, Tuholski, Laughlin, & Conway, 1999; Turner & Engle, 1989). This finding has led some authors to argue for the central role of processing (e.g., executive attention; Conway et al., 2003; Engle et al., 1999) in driving the correlation between WMC and g. Subsequent evidence, however, supports the central role of short-term storage (e.g., immediate recall of memory for numbers, letters, or visual arrays; Chuderski, Taraday, Nęcka, & Smoleń, 2012; Colom, Abad, Quiroga, Shih & Flores-Mendoza, 2008; Colom, Flores-Mendoza, Quiroga, & Privado, 2005).

The executive attention account of inter-individual differences in WMC (e.g., Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007) claims that individuals with low WMC have relatively limited capacity for controlling goal-directed attention, and for resolving response conflict, compared to individuals with high WMC. According to this view, high WMC individuals typically produce fewer errors on tasks such as the classic Stroop (1935) test (e.g., Kane & Engle, 2003; Long & Prat, 2002) because they possess relatively greater capacity for directing attention to naming the colour, and for resolving the competition between eliciting the prepotent (but incorrect) response of reading the word and producing the appropriate response of naming the colour in which the word is written. On the basis of this executive attention account the memory maintenance and retrieval theory of WMC has been developed (e.g., Unsworth & Engle, 2007a, 2007b; Unsworth & Spillers, 2010) which claims that high WMC individuals are better at both maintaining relevant information in primary (working) memory,

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and at using appropriate retrieval cues to retrieve information from secondary (long-term) memory when required. Other researchers stress that response inhibition is the single most important factor in individual differences in WMC (Hasher & Zacks, 1988; Lustig, May & Hasher, 2001; May, Hasher, & Kane, 1999). The claim is that individuals with high WMC are better at restricting WM access to task-relevant information, resolving response conflict, and inhibiting dominant but inappropriate responses. High WMC individuals therefore perform better on the Stroop because they are better able to limit WM access to the relevant task component (naming the colour) and at inhibiting the dominant but inappropriate tendency to name the word. In the context of the maintenance and retrieval view, this theory would also explain how conflict is resolved between the inappropriate stimulus-response mapping of reading the word held in secondary memory and the relevant but less prepotent mapping of stating the colour held in primary memory. The three accounts are not mutually exclusive and share overlapping theoretical claims, but they also incorporate distinct and testable predictions (Redick, Calvo, Gay, & Engle, 2011) as outlined below.

Performance on the Stroop is usually considered to reflect capacity for response inhibition and significant correlations between performance on the Stroop and psychometric intelligence have been reported (e.g., Dempster, Corkill & Jacobi, 1995; Polderman et al., 2009; Salthouse, Atkinson, & Berish, 2003). Functional magnetic resonance imaging (fMRI) studies indicate that the anterior cingulate is recruited in conditions of response conflict (Kerns et al., 2004), and by performance on tasks with high *g*-loadings such as Raven's Advanced Progressive Matrices (Gray, Chabris & Braver, 2003). Cognitive models of "general ability" (e.g., Das, 2002) and prefrontal cortex (Roberts & Pennington, 1996) also highlight the importance of inhibition in intelligence. Nevertheless, studies based on factor analysis have produced inconsistent findings. For example, Salthouse et al. (2003) report a strong relationship ($r = 0.73$) between their composite measures of inhibition and fluid intelligence in a large sample of adults ($N = 261$). Conversely, on the basis of evidence suggesting that executive functions—specifically, inhibiting prepotent responses, shifting between tasks/mental sets, and updating the contents of WM—are correlated but separable (e.g., Miyake et al., 2000; Miyake & Friedman, 2012), Friedman et al. (2006) observed that their composite measures of inhibition ($r = -0.11$) and shifting ($r = -0.08$) did not load significantly onto their fluid intelligence construct whereas WM updating did ($r = 0.74$; WM updating was operationalized by tasks that required the adding and deleting of information held in WM: keep-track, letter-memory, spatial 2-back). Other studies have demonstrated that WMC is not related to the ability to resist interference or dual-task coordination (e.g., Oberauer, Lange & Engle, 2004). These findings indicate that the correlation between response inhibition and intelligence is not straightforward, and therefore that interaction with some other task component(s) may be of critical importance in driving the relationship.

Redick et al. (2011) compared the executive attention, maintenance and retrieval, and inhibition theories of WMC in the context of go/no-go task performance. The authors compared two go/no-go tasks – a *simple* task involving a "go" response to one letter and a "no-go" response to all other letters (with a reverse mapping in another block), and a *conditional* task involving a go response to two letters conditional on the current target being different to the last. Differences between individuals with high/low WMC were observed only in the conditional task, such that high WMC individuals performed better on both target trials (target letters meeting the conditions for a go response) and lure trails (target letters meeting the conditions for a no-go response). Further, performance was significantly correlated with WMC in the conditional task only. These findings were interpreted in the context of the maintenance and retrieval account of WMC, with only the conditional task requiring active monitoring and updating of stimulus-response mappings, and the retrieval of the appropriate goal-relevant response. Redick et al. (2011) argue that if inhibition or executive attention were fundamental aspects of WMC, differences between individuals with high and low spans would also be observed in the simple task, because a prepotent response must be inhibited or response conflict resolved in both tasks.

An alternative view is that if attention is given to maintaining and updating the stimulus-response mappings, reduced attention is available for resolving the conflict associated with the no-go requirement, producing more error on these trials. Consistent with the notion of shared but limited resource availability for processing and storage requirements, research has shown that *anti*-saccade (Mitchell, Macrae, & Gilchrist, 2002; Roberts, Hager, & Heron, 1994) and motor response inhibition (Hester & Garavan, 2005) capacities decline with increasing WM load. Studies directly addressing storage versus processing accounts of the driving force in inter-individual differences in the WMC–*g* relationship emphasise the overarching importance of storage. For example, Colom et al. (2008) claim that simple short-term storage (i.e., memory for numbers/letters/visual arrays) accounts for a large proportion of the relationship between WMC and *g*, and that although attention control, WM updating, and mental speed are independently correlated with *g*, these relationships disappear when short-term storage is controlled for. In a related study, Chuderski et al. (2012) found that their storage latent factor (comprising memory for visual arrays, monitoring of relations among stimuli, and updating information in WM) accounted for 70% of the variance in measured fluid intelligence. For their three processing measures, only attention control, and neither resistance to interference nor response inhibition, was correlated with fluid intelligence (accounting for 25% of the variance in fluid intelligence), yet, when storage was controlled for, this correlation disappeared.

A visual change detection study (Fukuda, Vogel, Mayr, & Awh, 2010) has claimed that the number of representations that can be held in WM is highly correlated with fluid intelligence but that the resolution with which stimulus representations are stored in WM is largely independent. Nevertheless, observations by Duncan, Emslie, Williams, Johnson, & Freer (1996) indicate that the relationship between fluid intelligence and WM cannot be explained on the basis of a straightforward storage function. In their letter monitoring task, participants were able to recall all task requirements after task completion, but the sensitivity to fluid intelligence was explained by differences in the capability for responding appropriately to those requirements. Failure to produce the appropriate response (referred to as "goal neglect") was largely restricted to participants scoring > 1 SD below the sample mean on the Culture Fair test of fluid intelligence (Cattell, 1971; Cattell & Cattell, 1973).

Duncan et al. (2008) presented evidence that the efficiency with which a task is cognitively modelled or held in mind may be of more fundamental importance to the involvement of Spearman's *g* than the real time processing demands associated with the task. Across a series of computer based experiments, incorporating a variation of the task presented here (Bright, 1998), the authors showed that the form in which instructions were presented was the primary factor predicting both the level of goal neglect and the size of correlation between goal neglect and Spearman's *g*. Thus, although increased task complexity did not increase the level of neglect of task demands, an additional "dummy" requirement which had no impact on what participants were required to do during actual task execution increased level of neglect and the strength of the performance–*g* correlation. This pattern of results has been replicated in children using a slightly simplified version of this feature match task (Roberts & Anderson, 2014). On the basis of their findings Duncan et al. (2008) claim that the ability to attend to a complex "task model – a working memory description of the relevant facts, rules, and requirements used to control current behaviour" (p. 140) is fundamental to individual differences in *g* (see also Bhandari & Duncan, 2014; Dumontheil, Thompson & Duncan, 2010; Duncan, Schramm, Thompson, Dumontheil, 2012).

In the present study we explore the relationship between participants' effective modelling of task demands and Spearman's *g* in the context of other candidate "risk factors" for the recruitment of *g*. In