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When are fluid intelligence and working memory isomorphic and when are they not?☆

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ABSTRACT

Study 1 investigated whether the strength of correlation between latent variables representing working memory capacity (WMC) and fluid intelligence (Gf) depends on the time allowed to work on an intelligence test. When the half recommended time was given to fulfill two Gf tests, WMC and Gf were statistically indistinguishable, indicating that working memory and fluid intelligence are fully isomorphic constructs. However, when virtually no time limit was applied, WMC explained only 38% of variance in Gf. Further analyses suggested that only the latter testing conditions allowed low-capacity participants for relational learning during test taking, which allowed them to reduce their distance to high-capacity people. Study 2 corroborated the moderate value of WM–Gf correlation in untimed intelligence testing with a larger number of Gf and WM tasks, as well as showed that the indices of learning in a novel test of relation discovery predict significant amount of Gf variance. In sum, the research suggests that fluid reasoning can be differently related to WMC depending on the time pressure during Gf testing, and it also indicates that learning abstract relational representations may be an important component of unspeeded intelligence, but barely takes place during speeded testing.

1. Introduction

For more than a century (Binet, 1903; Galton, 1883; Spearman, 1904), the nature of general intelligence (*g* factor), the theoretical construct reflecting vast interindividual variability but high intraindividual consistency in coping with diverse cognitive tasks, has been one of the central research problems of psychology and neuroscience. Its importance is highlighted by the fact that *g* has been found to strongly predict educational, professional, and personal success (or lack of it) in everyday life (e.g., Deary & Der, 2005; Gottfredson, 1997; Sternberg, 1996).

A crucial finding in research on the structure of human intellect (e.g., Cattell, 1971; Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004; Gustaffson, 1984; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002) is that *g* factor seems to rely to a great extent on fluid intelligence (Gf factor, also referred to as fluid ability, reasoning ability, or fluid reasoning). Gf reflects the ability to use abstract relational reasoning in order to solve novel problems, in which prior experience and learned knowledge are of little use. Great efforts have been devoted to the identification of the neuronal and cognitive mechanisms which determine scores on Gf tests, including the well-known Raven's Advanced Progressive Matrices test (Raven, 1962; Raven for short). Apart from fulfilling the scientific goal of explaining the nature of human intelligence, such a finding could also provide researchers with methods for increasing fluid ability (Jaeggi et al., 2010; Klingberg, 2010), which would be especially desirable for the compensation of cognitive deficits in some groups of people, like the mentally deteriorated (Holmes, Gathercole, & Dunning, 2009) or ADHD children (Klingberg, Forssberg, & Westerberg, 2002) as well as healthy aging persons (Schmiedek, Lövdén, & Lindenberger, 2010).

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So far, the most important conclusion drawn from the research on the neurocognitive basis of fluid intelligence shows that the capacity of working memory (WM) is its strongest predictor. WM denotes processes and mechanisms responsible for the active maintenance and transformation of information crucial for the current goal/task/operation, occurring within a time scale of several seconds (Baddeley, 2007). WM is usually assessed with tasks requiring the encoding, storage, and recall or recognition of stimuli. WM capacity (WMC) has been operationalized as the direct number of items that a person can reproduce (Engle & Kane, 2004), or the indirectly estimated number of items that one is presumed to keep in WM (Rouder, Morey, Morey, & Cowan, 2011). The most surprising finding concerning WMC is the fact that, most probably, human WM is able to reliably store in parallel only a few items at best. Average capacity has been estimated to be four items (Luck & Vogel, 1997), and it seems to vary in people from two to six items (Cowan, 2001). Early studies assumed that proper estimation of WMC has to require some form of concurrent processing (i.e., complex span tasks; Engle & Kane, 2004), but recently it has been suggested that tasks without any processing component (i.e., simple span or short-term memory tasks; STM tasks) are also excellent measures of WMC as well as good predictors of Gf (e.g., Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Oberauer, 2005; Unsworth & Engle, 2007). Due to the possibility of significant measurement errors and task-specific variance reflected by WM scores, WMC is usually not derived from a single WM task, but instead is assessed on the basis of scores from several WM tasks. The strength of correlation between Gf and WMC is usually estimated on the latent variable level, with the use of confirmatory factor analysis (CFA) and/or structural equation modeling (SEM).

1.1. The strength of the Gf–WM relation and its explanations

Many studies have investigated the precise strength of the relation between Gf and WMC. The results of most of these studies indicate that both constructs are at least moderately correlated, with *r*s usually falling in the .30–.80 range (e.g., Ackerman, Beier, & Boyle, 2005; Buehner, Krumm, Ziegler, & Pluecken, 2006; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Friedman et al., 2006; Kane et al., 2004; Kaufman, DeYoung, Gray, Brown, & Mackintosh, 2009; Shelton, Elliott, Matthews, Hill, & Gouvier, 2010; Unsworth, 2010; Unsworth, Brewer, & Spillers, 2009; Unsworth, Spillers, & Brewer, 2010; Unsworth, Miller et al., 2009).

The lower-level mechanisms underlying the variance shared by the Gf and WMC latent variables have been hotly debated. One of the proposals suggested that both variables can be explained by the differences in mental speed, for example assessed with simple perceptual-motor tasks involving stimuli comparison (for reviews see Jensen, 2006; Sheppard & Vernon, 2008). Such an explanation seems to be valid with regard to Gf tests administered under severe time constraints, in which the speed of mental operations may determine if a participant is able to attempt all Gf test items or not (Wilhelm & Schultze, 2002), and so the strong intercorrelation of Gf and mental speed can simply be attributed to the shared method variance. However, mental speed indices also seem to correlate with scores on unspeeded (i.e., power) tests (Jensen, 2006). Another explanation for the WM–Gf link pertains to the sheer storage capacity of the active and highly accessible memory buffer (called primary memory or the focus of attention). Individual Gf level has been related to the number of elements (Colom et al., 2008; Cowan et al., 2006), the number of temporary bindings among elements (Oberauer, Süß, Wilhelm, & Sander, 2007), or the number of variables within a relation describing elements (Halford, Cowan, & Andrews, 2007) that such a buffer can simultaneously maintain and/or process. Evidence for the contribution to the WMC and Gf of both mental speed and storage capacity is vast, but their estimates are often intercorrelated (e.g., Ackerman, Beier, & Boyle, 2002; Conway et al., 2002; Süß et al., 2002).

Consequently, it is currently disputed which of these factors is a genuine predictor of Gf and which is not. Some theorists (e.g., Jensen, 1998; Salthouse, 1996) proposed that mental speed determines storage capacity, because representations in WM quickly decay, and the faster these representations can be processed before falling below a retrieval threshold, the more of them can be recalled, bound, or related. However, such theories assume that decay in memory really exists, while many studies question the role of decay in forgetting (e.g., Lewandowsky & Oberauer, 2009; Saito & Miyake, 2004). Moreover, the variables reflecting capacity usually correlated with Gf more strongly than the variables reflecting speed (e.g., Colom et al., 2008; Conway et al., 2002; Kaufman et al., 2009; Martínez et al., 2011). So, Wilhelm and Oberauer (2006) argued that storage capacity determines psychometric speed, because tasks that measure speed require active storage of stimulus–response (S–R) bindings, and as storage capacity is very limited, the low-capacity persons often lose the required S–R bindings from their buffer, therefore requiring additional time to restore these bindings, and so leading to prolonged response latencies, especially when bindings are arbitrary.

The debate is far from being settled, and the relations between speed and capacity may be even more complex (see Rypma & Prabhakaran, 2009) than in the views presented above. Moreover, there could be another factor that determines both speed and capacity. For example, one proposal pertains to attention control (Engle & Kane, 2004; Vogel, McCollough, & Machizawa, 2005), which consists of focusing attention on task-relevant information while blocking distraction and interference. Effective control may be crucial not only for storage capacity, as only relevant elements/bindings/relations are maintained in the active buffer (so available capacity is used optimally), but also for processing speed, as irrelevant elements do not capture attention (so no time needs to be wasted for overriding the capture).

Furthermore, if the strength of correlation between WMC and Gf really amounts to a value that falls between $r = .30$ and $r = .80$, then the underlying factor, regardless of what it really is, will explain only part of the variance shared by both these constructs (probably half of it; see metaanalysis done by Kane, Hambrick, & Conway, 2005). Thus, an interesting question concerns the other part of this variance, which is unexplained by WMC. What factor could be related to fluid intelligence above and beyond WMC? One alternative is that more intelligent people possess more efficient learning abilities. Indeed, recent research has found that associative learning contributes to Gf independently from WMC (Kaufman et al.,