Intelligence 66 (2018) 44–53

Contents lists available at ScienceDirect

Intelligence

journal homepage: www.elsevier.com/locate/intell

The strong link between fluid intelligence and working memory cannot be explained away by strategy use

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ABSTRACT

In order to evaluate recent claims that individual differences in strategy use (i.e., using either constructive matching or response elimination to solve a *gf* problem) can explain away, or at least significantly weaken, the strong relationship between working memory capacity (WMC) and fluid intelligence (*gf*), in two large-sample studies we applied multiple measures of WMC, *gf*, and strategy use, and tested if the mediation of strategy use affected the WMC-*gf* relationship. We observed no significant drop in the WMC-*gf* link due to mediation, thus refuting the alleged role of strategy use in the involvement of working memory processes in fluid reasoning. Moreover, our results suggest that it is the significant correlation of both strategy use and cognitive style with WMC which is the driving force for their moderate correlation with *gf*.

1. Introduction

Fluid intelligence (*gf*) is usually measured by means of knowledge-lean problems which require abstract reasoning (McGrew, 2009). A typical *gf* problem requires to induce hidden rules and patterns that govern stimuli as well as to apply those rules/patterns in order to choose the best response out of several potential options. Probably the best known and most widely used *gf* test is Raven's Progressive Matrices (Raven, 1938; Raven, Raven, & Court, 1998), which consists of items that include a three-by-three matrix of figural patterns missing the bottom-right pattern as well as eight response options with the patterns that can potentially match a missing one. The task is to discover all the rules that govern the matrix (e.g., distribution of features, progression of a feature, a logical operation such as OR, AND, and XOR, etc.), and to choose the pattern that validly completes the matrix. Items difficulty progresses throughout the test, yielding accuracy from ceiling to floor. A well-known taxonomy of *gf* tests (Snow, Kyllonen, & Marshalek, 1984) suggested that the Raven test's loading on the *gf* factor is probably the highest among all known intelligence tests. In consequence, several analogues of the test (e.g., BOMAT; Hossiep, Turck, & Hasella, 1999), especially with normed items generated by an algorithm (Arendasy & Sommer, 2005; Embretson, 1998; Matzen et al., 2010) were developed. Other high-loading *gf* tests include paper folding, arithmetic reasoning, completing letter/number/geometric series as well as making verbal and geometric analogies (Snow et al., 1984).

Researchers proposed numerous theories and models (including computational ones) which attempted to explain what sort of cognitive processes are involved in successful performance on *gf* tests, and why people vary in such performance (e.g., Carpenter, Just, & Shell, 1990; Chuderski & Andrelczyk, 2015; Hummel & Holyoak, 1997; Rasmussen & Eliasmith, 2014). These theoretical proposals converge to the explanation of variance in *gf* in terms of variation in working memory capacity (WMC). Working memory (WM) is a postulated neurocognitive mechanism responsible for highly active and easily accessible but short term and capacity limited maintenance of task-relevant information (Cowan, 2001). Usually, individual WMC is assessed with complex span tasks (Conway et al., 2005), but other tasks that block chunking and rehearsal, such as visual storage tasks and updating tasks, were also shown to be apt measures of WMC (Oberauer, 2005). In order to solve a *gf* test problem, a person may need to represent in WM all crucial aspects of the problem and its solution. Only if WMC is sufficient, the right solution can be developed and matched to the correct response option. Although precise mechanisms limiting WMC are disputed, encompassing the maximum number (Cowan, 2001) and reliability (Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004) of objects in WM, their binding (Oberauer, Süß, Wilhelm, & Wittman, 2008), their transfer to/from long-term memory (Unsworth & Engle, 2007), as well as control over them (Kane & Engle, 2002), the strong links between WMC and *gf*, ranging from half (Kane, Hambrick, & Conway, 2005; Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth, Redick, Lakey, & Young, 2010) to total variance shared (Chuderski, 2015; Colom et al., 2004; Oberauer et al., 2008), suggest that effective processing of *gf*

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https://doi.org/10.1016/j.intell.2017.11.002
Received 21 September 2017; Received in revised form 24 October 2017; Accepted 6 November 2017
Available online 21 November 2017
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problems requires efficient underlying WM mechanisms.

In contrast, some researchers proposed that scores on *gf* tests are not determined by such mechanisms, but result from different strategies adopted by participants when solving *gf* problems, with some strategies being very effective whereas other leading to deteriorated performance. In a seminal eye-tracking study of performance on a visual analogy problem, Bethell-Fox, Lohman, and Snow (1984); see also Snow, 1980) identified two qualitatively different strategies of coping with the task. Some participants devoted majority of time to the problem, scanning it in a systematic manner, and possibly constructing mentally the most likely solution, which then could be compared with existing response options (so-called constructive matching). Other participants processed the problem elements in a less systematic way, frequently switching back and forth between the problem and the response options, probably from the very start testing whether some options could be rejected (so-called response elimination; see also Schiano, Cooper, Glaser, & Zhang, 1989). Constructive matching resulted in higher solution rates than response elimination. These two strategies were also found in the case of Raven's Matrices (Carpenter et al., 1990; Hayes, Petrov, & Sederberg, 2011; Mitchum & Kelley, 2010; Vigneau, Caissie, & Bors, 2006). Response elimination seems to be a fallback strategy for low-performing people, and presence of this strategy undermines the validity of a problem as a *gf* test. When the chance to eliminate responses was reduced either by presenting erroneous response options that were so similar to the correct option that they could not be easily distinguished (Arendasy & Sommer, 2005), or by requiring to draw a response from scratch (in a free response *gf* test; Becker et al., 2016), the *gf* loading of a matrix test substantially increased. Strategy use can also be improved by training (Hayes, Petrov, & Sederberg, 2015) and instruction (Leosche, Wiley, & Hasselhorn, 2015).

One factor that might lead to strategical differences in coping with *gf* test items might be cognitive style: Some people may systematically process information in such items because they generally display more reflective, mindful, analytical approach to information. Cognitive dispositions related to epistemic motivation, such as need for cognition (intrinsic motivation to engage in cognitively demanding activities), and a tendency to engage in analytic thinking (in opposition to relying on intuition), are not only positively related to intelligence, but may predict different cognitive biases and behaviors when *gf* is controlled for (Cacioppo, Petty, Feinstein, & Jarvis, 1996; Pennycook, Fugelsang, & Koehler, 2015). Another thinking disposition, open minded thinking (flexibility and openness in face of alternative views and perspectives), also correlates with intelligence and predicts the quality of reasoning (Stanovich & West, 1997). Thus, such general cognitive dispositions may also, at least to some extent, explain the strategy differences as well as the effort put in solving intelligence tests.

Another possibility is that developing a given strategy in a *gf* test might simply depend on available WMC, with more WMC required for constructive matching, while response elimination being less dependent on WMC. For example, a person with low WMC, who is not able to construct reasonable responses to a given set of problems, will likely turn to the eliminative strategy, and at least will try to identify the most likely response. Indeed, an eye-tracking study indicated that low-WMC people switch between the Raven matrix and the response options more often than do high-WMC people (Jarosz & Wiley, 2012). It is also possible that cognitive style and WMC affect the strategy use in some interaction, for instance the reflective style motivates participants to start constructive matching, whereas high WMC gives them the necessary mental resources to continue this strategy, allowing to avoid the need for response elimination.

A recent study (Gonthier & Thomassin, 2015) examined the mutual relationships between the Raven score, WMC as assessed with the complex span, and strategy use. The study concluded that strategy fully mediated the link between Raven and WMC. In the first experiment, the Raven scores of a group who was instructed to apply constructive matching correlated more weakly with WMC ($r = 0.20$) than the scores of a control group who received no instruction ($r = 0.33$). The second study measured strategy use by means of a questionnaire, and showed with the regression model that, when the original link between Raven and WMC equaling $r = 0.33$ was mediated by strategy, the link dropped to non-significant $r = 0.13$. If the contribution of WMC to *gf* consisted solely on affecting the adopted strategy, our understanding of what *gf* is might need substantial revision: The role of neurocognitive mechanisms in performance on *gf* tests would be less critical, whereas the role of strategical learning and instruction would be more important (e.g., Kaufman, 2013; Nisbett, 2015). This very possibility might be suggested by studies which showed that prior experience to Raven's Matrices visibly improved subsequent performance (Chuderski, 2013, 2016; Hayes et al., 2015; Ren, Wang, & Schweizer, 2014). Moreover, such a possibility would yield important practical consequences: there would be room for improving thinking and reasoning skills with proper techniques (Nisbett, 2015).

However, several aspects of the Gonthier and Thomassin study do not allow for jumping to such conclusions. First, the original effect between Raven and WMC equaling $r = 0.33$ was relatively weak, taking into account that zero-order correlations above $r = 0.4$ are frequently reported (e.g., Chuderski, 2014; Shipstead et al., 2014; Unsworth et al., 2010). Thus, such a weak link could be easy disrupted by additional predictors in a regression model, while when being stronger it might have retained statistical significance. One possible cause for this link's weakness might be a highly restricted student sample, whose WMC ranged only from -1.5 *SD* to 1.5 *SD*, whereas in the general population the doubled range would be expected. Second, in fact neither the drop from $r = 0.33$ to $r = 0.20$ in the first experiment nor the decrease from $r = 0.33$ to $r = 0.13$ in the second study were significant in terms of most of the conventional statistical tests (the latter fact was related to the small sample, counting only 93 people). So, it is not certain if the effect reported by Gonthier and Thomassin was robust enough. In consequence, no decisive data on the contribution of strategy use to the relationship between WMC and *gf* exists to date. Two studies presented below aimed to fill this gap by bringing a reliable estimation of the amount of variance shared between WMC and *gf* that can be explained away by the differences in the self-reported strategy used to cope with *gf* tests.

1.1. Study 1

This study aimed at directly replicating Gonthier and Thomassin's (2015) Experiment 2, with only two technical improvements. First, the sample size was tripled in order to gain sufficient statistical power to detect significant differences in correlation strength of at least $\Delta r = 0.19$, with $\alpha = 0.05$ and $1 - \beta = 0.95$ (according to G*Power 3.1.9.2 software; Faul, Erdfelder, Buchner, & Lang, 2009). Also, these participants were recruited via internet (i.e., were not solely students). Second, instead of using one compound WM task (as in the original experiment), we used three full-blown complex span tasks (with letter, number, and figural material to be recalled), and computed the WMC factor by means of factor analysis. Such factors reflect almost perfect reliability, as compared to compound scores. Combined with a more variable sample, the WMC factor values nicely ranged from almost -4.0 *SD* to almost 2.0 *SD*.

1.2. Participants

Three hundred and eighteen volunteers (216 women, 102 men) were recruited via internet advertisements, and were paid the equivalent of 20 euros in Polish zloty. The mean age was 24.5 years (*SD* = 6.02, range 18–46). All participants had normal or corrected-to-normal vision. All participants signed an informed consent, were provided with a general information that the study investigates human thinking, their data would be anonymous and not diagnostic in any way, and they could leave the laboratory at will at any moment.

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