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The broad factor of working memory is virtually isomorphic to fluid intelligence tested under time pressure

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ABSTRACT

How much overall variance in fluid intelligence (Gf) can be predicted by four working memory (WM) functions: storage capacity, attention control, relational integration, and updating was investigated under time pressured Gf testing. Confirmatory factor analysis indicated that the broad WM factor, which was subsumed by these four WM functions, shared 83.4% of variance with Gf tested under pressure, whereas a reanalysis of previous data with the same model showed that only 58.2% variance was shared with virtually untimed Gf tests. Moreover, in timed Gf tests, only the easiest, early items contributed to the WM-Gf correlation, whereas in untimed tests also the hardest, late items were linked with Gf. These results suggest that the measurement of "fast" intelligence primarily taps the functions of WM, whereas "slow(er)" intelligence depends also on some other cognitive processes beyond WM.
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1. Introduction

Fluid intelligence (fluid reasoning, reasoning ability; Gf), which consists of using reasoning to solve novel abstract problems that cannot be solved on the basis of existing knowledge, is an important component of human general intelligence. Because of strong predictive power of Gf for such psychological variables as socio-economical status (academic, professional, financial, etc.), one of the most important themes in psychology consists of identification of mechanism underlying Gf.

Probably the strongest known predictor of fluid intelligence is the capacity (WMC) of working memory (WM) – the neurocognitive mechanism responsible for the active maintenance and transformation of the limited amount of information in service of the current task. There are several theories on what in WMC makes it so strongly correlate with Gf. One theory (Kane & Engle, 2002) assumes that individual performance in both WM tasks and Gf tests depends on *attention control* exerted over cognitive processes, which includes goal-driven directing attention and filtering out distraction. Alternatively, it was shown that performance on sheer *storage* tasks, which require little attention control, was also a very good predictor of Gf (Cowan, 2001), probably because an individual needs to keep the subproducts of reasoning in the most accessible part of WM. WM may also play an important role in Gf because it affects what relations can be constructed among WM items. Notably, Oberauer, Süß, Wilhelm, and Wittman (2008) proposed that crucial for Gf is *relational integration*, which consists of the construction of flexible, temporary bindings between a number of chunks held in WM, in order to develop a more complex, relational structure. The tasks that require participants to detect simple relations have been shown to be excellent predictors of WMC and Gf (Chuderski, 2014; Oberauer et al., 2008). Finally, also proper *updating* of WM contents, that is, their substitution and transformation in line with the demands of the current task, has been indicated as a key WM function (Jonides & Smith, 1997).

Although each listed WM function probably contributes to Gf to some extent (see Conway, Getz, Macnamara, & Engel de Abreu, 2011), the question of precisely *how much variance in Gf can be explained by the broad WM construct* (e.g., including all four above mentioned WM functions) have not received a univocal answer. Metaanalyses demonstrated that WMC usually explains between half (Kane, Hambrick, & Conway, 2005) and three quarters (Oberauer, Schultze, Wilhelm, & Süß, 2005) of Gf variance. At the same time, some studies reported Gf-WM correlations below $r = .30$ (e.g., Kaufman, DeYoung, Gray, Brown, & Mackintosh, 2009; Unsworth, Spillers, & Brewer, 2010). Finally, some studies reported WMC to be isomorphic to Gf (e.g., Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004; Martínez et al., 2011; Oberauer et al., 2008). Thus, the question whether Gf reduces or not to the effectiveness of WM functioning remains open.

Attempting to answer this question, Chuderski (2013) has suggested that how much Gf variance is determined by WMC depends

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on time pressure during intelligence testing. When Gf tests were administered in strict time limit (e.g., 20 min for Raven APM), WMC and Gf were statistically indistinguishable (i.e., isomorphic), whereas when ample time was given (e.g., one hour for APM), WMC predicted only one third of Gf variance. These results suggest that time pressure somehow blocks longer lasting and more complex cognitive processes contributing to reasoning, and under such pressure people have to rely on simultaneous, online manipulation of stimuli, primarily using their WM resource. However, this study had one major drawback related to the fact that it relied on the reanalysis of already existing datasets. In result, the WM-Gf isomorphism under pressure has been shown with regard to only two WM tasks: a letter variant of storage task, and a number variant of relation integration task (no non-verbal task was used). In result, the WM-Gf isomorphism could be objected, as the strong correlations found might have resulted from unknown peculiarities of the WM tasks used that made these tasks in some way highly similar to the timed Gf tests. Although, Experiment 2 replicated a moderate WM-Gf link with more WM tasks, in this study only virtually untimed Gf was examined, but not timed. These results are important because, although most of Gf tests' instructions recommend a reasonable time allowed (e.g., 40 min in APM) that yields a good compromise between power and speed, in the substantial number of studies on the WM-Gf relation (almost 50%; see Chuderski, 2013, Table 1) this time was strongly reduced. At the same time, several such studies (see ibidem) that were highly influential used unlimited administration time. Thus, it seems important to know the psychometric and theoretical consequences of using non-standard administration times in intelligence testing for the research on WM and Gf.

The goal of the present study was to replicate and extend the Chuderski results by evaluating the strength of link between Gf, tested under time pressure, and the broad WM construct, measured by as much as eight WM tasks, reflecting four above presented WM functions, and both verbal and non-verbal types of stimuli. In line with the previous results, it was expected that the link between timed Gf and WMC is close to unity, reflecting the possibility that solving timed Gf problems requires primarily simultaneous maintenance and online manipulation of information – the same processes that are also required for the WM performance. Moreover, as the same WM and Gf tests were used here and in Chuderski (2014), where virtually untimed Gf tests were applied, we were able to reanalyze the latter data using the model fitted in the present study (reflecting the broad WM latent variable loading the four WM functions), and in result we could test more reliably whether the link between the broad WM latent variable and timed Gf is indeed significantly stronger than for untimed Gf.

Table 1
Descriptive statistics for working memory and fluid intelligence measures ($N = 264$).

Task	*M*	SD	Range	Skew	Kurt.
Color arrays	3.61	1.27	−1.97 to 6.30	−0.94	1.90
Letter arrays	3.28	1.44	−2.05 to 6.12	−0.47	−0.03
Arrow antisaccade	0.78	0.21	0.02–1.00	−1.52	1.97
Letter antisaccade	0.83	0.20	0.02–1.00	−1.95	3.66
Same relation	0.69	0.18	−0.15 to 0.95	−1.36	2.46
Different relation	0.30	0.23	−0.23 to 0.78	−0.39	−0.77
Figural 2-back	0.69	0.18	0.00–0.95	−1.19	1.99
Number 2-back	0.81	0.17	0.00–1.00	−1.61	3.93
Raven APM	19.07	5.38	1–31	−0.62	0.41
Paper analogies	18.54	5.65	3–34	0.05	−0.16
Computerized analogies	0.20	0.14	0.00–0.83	0.78	1.03

Note: The arrays task score = the mean number of items held in WM. The antisaccade, *n*-back, relation monitoring (same/different relation), and computerized analogies scores = proportion correct. The Raven and paper analogies scores = the number of correctly solved items.

2. Method

Three highly timed intelligence tests were administered. All participants attempted also the battery of eight WM tasks, two (one verbal and one non-verbal, except for the relational integration tasks, in which verbal and non-verbal aspects were combined) per each above mentioned function of WM (storage, updating, control, and integration), thus measuring the broad WM construct to a large extent. The four types of tasks used are schematically presented in Fig. 1, and described below.

2.1. Participants

A total of 264 volunteer participants (166 women) were recruited via publicly accessible social networking websites. Each participant gave informed consent, was told that he or she can leave the experiment at will and at any moment, and was paid the equivalent of 15 euro in Polish zloty. The mean age of participants was 23.2 years ($SD = 4.4$, range 18–46). Another four participants were excluded from analysis due to missing some tasks.

2.2. Measures of fluid intelligence

Two paper-and-pencil tests of reasoning were applied, the widely used Raven Advanced Progressive Matrices (Raven, Court, & Raven, 1983), and a figural analogy test (for description of the test see Chuderski, 2014). Half of the standard administration time was allowed for each test (20 and 16 min, respectively). Also, a computerized figural analogy test including 16 items was applied (for description of the test see Chuderski, 2015a), with 2 min allowed per item (in comparison to 4 min used in Chuderski, 2014). The total number of correct answers in each test was taken as a respective score.

2.3. Storage tasks

Two variants of an array-comparison task were used. Each variant consisted of 90 trials. On each trial a virtual 4×4 array was filled with five to nine stimuli, picked from a set of ten Greek symbols (e.g., α, β, χ, and so on), or colored squares (i.e., the letter and color variants of the task, respectively), then followed by a black square mask of the same size as the array, presented for 1.2 s, and then another array was shown. In a random 50% of trials, the second array was identical to the first; in the remaining trials the second array differed from the first by exactly one item in one position, which was always a new item (not a duplicate of an item from another position). The task was to press one of two response keys to indicate whether the highlighted item was the same or different in the two arrays. The tasks were self-paced.

2.4. Attention control tasks

Two variants of the antisaccade task were used, measuring the attention control ability, each consisting of 40 self-paced trials. Each test trial consisted of four events. First, a cue was presented for 1.5 s to prompt subjects to look at the side opposite to a rapidly flashing black square. Next, a fixation point was presented in the center of the screen for 1–2 s. Then, the flashing square was shown in the middle of the left or right side of the screen, about 16 cm from the fixation point, for 0.15 s. Finally, a small dark gray arrow or a string was presented in the middle of the opposite side of the screen to the square for only 0.2 s before being replaced by a mask. The task was to look away from the flashing square in order to observe the direction of the arrow or the identity of the string and press the associated key.

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