Personality and Individual Differences 74 (2015) 241–247

Contents lists available at ScienceDirect

Personality and Individual Differences

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

Do processing speed and short-term storage exhaust the relation between working memory capacity and intelligence?

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ARTICLE INFO

Article history:
Received 13 June 2014
Received in revised form 8 October 2014
Accepted 9 October 2014
Available online 14 November 2014

Keywords:
Processing speed
Short-term storage
Working memory capacity
Fluid intelligence
Crystallized intelligence

ABSTRACT

The roles of processing speed (PS) and short-term storage (STM) for explaining the relationship between working memory capacity (WMC) and intelligence are analyzed at the latent variable level. 253 Chinese college students completed thirty-two measures from different content domains tapping the cognitive constructs of interest. The key findings showed that (a) PS accounts for the relationship between WMC and fluid intelligence, (b) STM and PS are required for explaining the correlation between crystallized intelligence and WMC. Therefore, this study provides support for the view that PS underlies the correlation between WMC and intelligence, yet with the nuance that its relevance decreases when cognitive tasks rely on crystallized knowledge and skill.

1. Introduction

Working memory capacity (WMC) has consistently shown high correlations with intelligence (or general cognitive ability) at the latent variable level (e.g., Dang, Braeken, Colom, Ferrer, & Liu, 2014; Martinez et al., 2011; Oberauer, Schulze, Wilhelm, & Süß, 2005). Yet, the causes underlying these relations are still elusive (Hunt, 2011). WMC involves simultaneous processing and storage, and therefore its correlation with intelligence might be based on either one of those cognitive facets or on shared resource requirements. Although a lot of subcomponents can be considered, processing speed (PS) and short-term storage (STM) can be considered as the most basic non-storage and storage components of the WMC system. Similarly, for intelligence, different subcomponents relying on distinguishable cognitive requirements can also be considered. For instance, fluid intelligence (Gf) is based on abstract reasoning mental processes, whereas crystallized intelligence (Gc) requires acquired cultural knowledge.

1.1. Processing speed

PS evaluates how fast basic cognitive functions are completed and is typically measured by tasks involving item identification, discrimination, or basic reaction times (Jensen, 2006). There is some consensus about the fact that people showing high Gf scores also provide faster reaction times and better WMC scores (e.g., Bjorklund, 2005). This has been addressed in both individual differential (e.g., Ackerman, Beier, & Boyle, 2002) and developmental research (e.g., Coyle, Pillow, Snyder, & Kochunov, 2011; Kail, 2000; Demetriou et al., 2013). For instance, PS is a remarkable biomarker of cognitive aging (Deary, Johnson, & Starr, 2010), and the age-related improvement in WMC might be mainly attributable to improvements in the speed component of the WM system (Fry & Hale, 2000). Nearly three fourths of the improvement in WMC was mediated by developmental changes in PS, and almost half of the age-related increase in Gf was mediated by developmental changes in PS and WMC (Fry & Hale, 1996).

1.2. Short-term storage

Besides those research stressing the role of PS, there is also research supporting the view that the correlation between WMC and intelligence can be exhausted by the simple storage component of the former (Colom, Flores-Mendoza, Quiroga, & Privado, 2005; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Hornung, Brunner, Reuter, & Martin, 2011). Martinez et al. (2011) analyzed such simultaneous relations and concluded that the nuclear intelligence component can be largely identified with basic and general STM processes, in contrast to the remaining processing

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http://dx.doi.org/10.1016/j.paid.2014.10.012
0191-8869/

components. Chuderski, Taraday, Nęcka, and Smoleń (2012) found that all storage tasks predicted, on average, 70% of variance in Gf, but other processing tasks were not substantially related to Gf. The re-analysis reported by Colom, Rebollo, Abad, and Shih (2006) of several previously published datasets revealed that it is difficult to distinguish between STM and WMC on strictly empirical grounds. This result was further supported by Unsworth and Engle (2007a) with the conclusion that simple and complex span tasks largely measure the same basic subcomponent processes. This finding indirectly supports the role of STM in the relation between WMC and intelligence.

STM and PS were also stressed simultaneously in some reports. For instance, reasoning ability can be explained by STM and mental speed, Krumm et al. (2009), short -term storage and mental speed account for the relationship between working memory and fluid intelligence (Burgaleta & Colom, 2008). Nevertheless, there is also conflicting research (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002) suggesting that the best predictor of general fluid intelligence is neither STM capacity nor PS. Along these lines, Redick, Unsworth, Kelly, and Engle (2012) failed to find support for the conclusion that PS underlies the correlation between WMC and Gf.

1.3. The present study

It remains difficult to achieve solid conclusions regarding the roles of STM and PS, underlying the relation between WMC and intelligence. To some extent, this diversity of findings might be a consequence of the specific operationalization of the constructs of interest. For addressing the question of whether or not PS and STM are relevant components of the WM system for predicting individual differences in intelligence, two type of studies are relevant: (a) those systematically varying the operationalization of the cognitive components to explore which measurement-specific aspects determine the heterogeneity of results, and (b) broad studies focusing on key cognitive components at the construct level using comprehensive sets of tasks.

Using this latter perspective, the present study uses a comprehensive measurement battery with the goal of obtaining representative estimates of the cognitive constructs of interest, namely, PS, STM, and WMC, along with Gf and Gc. The dataset is an expansion of a previous study (Dang, Braeken, Ferrer, & Liu, 2012; Dang, Braeken, Colom, Ferrer, & Liu, 2014).

The primary research question of the paper is whether WMC is still related to intelligence after the contributions of PS and STM are accounted for. In the analytic approach, predictors will be added to the regression equation for intelligence following a complexity rule beginning with PS, continuing with STM, and ending with WMC. If the residual variance in WMC no longer predicts intelligence differences when PS and STM are taken into account, then the hypothesis that PS and STM exhaust the relation between WMC and intelligence will be supported. Otherwise, results would be consistent with the perspective that the link between WMC and intelligence includes something extra, besides PS and STM. The findings should help to better define the domain and unique features of these cognitive constructs.

2. Method

2.1. Participants

Participants were college students ($n = 253$) from three Chinese universities and consisted of native Chinese speakers, aged between 18 and 22 ($M = 19.03$, SD = .86; 56% male, 44% female). The sample is relatively diverse and contains participants from a broad range of majors (i.e., arts and science). Participants were recruited through campus advertising. Participants received payment for their participation, with written informed consent obtained prior to the study.

2.2. Measures

A comprehensive battery of 25 cognitive tasks was compiled, resulting in 32 cognitive measures: 14 tasks assessing PS, 6 tasks assessing STM, 6 tasks assessing WMC, and 6 tasks assessing intelligence. A summary blueprint of the test battery is given in Table 1. Due to space restrictions, the detailed description of every task is given in the Supplementary material.

PS was measured by seven paper-and-pencil tasks adapted from the Woodcock–Johnson tests of Cognitive Ability (Woodcock, McGrew, & Mather, 2001). These tasks placed minimal demands on memory and attention, and were chosen to cover four construct domains (sensory-motor, pattern perceptual, symbol perceptual, and digit scanning speed). Each task was administered under timed conditions (i.e., 30 s time limit) twice (with different stimuli) such that participants obtained a total of $2 \times 7 = 14$ PS test scores. ***STM*** was measured by six tasks: three visual–spatial and three verbal–numerical, requiring the temporary maintenance of simple items for later recall. To make the tasks as simple as possible, single letters, digits, words, dots and blocks were used, instead of more complex stimuli. ***WMC*** was measured by six tasks, three being visual–spatial and three verbal–numerical, using the dual-task paradigm requiring both processing as well as storage of simple items for later recall. ***Intelligence*** was measured by six tasks. Specifically, *Gf* was measured by Raven's advanced progressive matrices (Gf1; Chinese version: Zhang & Wang, 1989) and Cattell's culture fair intelligence test (Gf2; Chinese version: Zheng, 1995). *Gc* was measured by four subtests of the Wechsler Adult Intelligence Scale (WAIS; Chinese version: Gong & Collaborative group of revising Wechsler Adult Intelligence Scale, 1992) – Information (Gc1), Similarities (Gc2), Vocabulary (Gc3), and Comprehension (Gc4).

2.3. Procedure

PS, Gf, and Gc tasks were administered using paper-and-pencil in accordance with standardized instructions; STM and WM tasks were administered with an IBM T30 compatible laptop using the specifically developed Memory Span Measurement Software.[1] Each participant was tested individually in the Cognitive Neuroscience Laboratory of Nanjing Normal University, with individual sessions lasting on average 2.5–3 h (including two breaks).

2.4. Data analysis

We used a structural equation modeling approach to formalize and test the primary research question. In line with the blueprint of the cognitive battery, a second-order confirmatory factor analysis model was constructed (Fig. 1). A Cholesky structural model was used for a hierarchical decomposition of the cognitive component constructs PS, STM and WMC and their effects on intelligence (see Loehlin, 1996; de Jong, 1999). The procedure allows for an orthogonal decomposition of explained variance and is conceptually similar to hierarchical regression (e.g., Cohen, Cohen, West, & Aiken, 2003) in a non-SEM context. All models were specified starting from the covariance matrix and fitted using full information maximum likelihood through the Lavaan library (Rosseel, 2012) in the statistical software R (R Development Core Team., 2014). Model fit was evaluated based upon commonly recommended fit

[1] Memory Span Measurement Software was designed by the Cognitive Neuroscience Lab of Nanjing Normal University (Chang Liu, Cai-Ping Dang, En-GuoWang, Xiao-Jiang Zhang, Hui-Ling Tang and Yun Tian).