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Neuroanatomic overlap between intelligence and cognitive factors: Morphometry methods provide support for the key role of the frontal lobes

Roberto Colom [a,b,*], Miguel Burgaleta [a,e], Francisco J. Román [a], Sherif Karama [f], Juan Álvarez-Linera [b], Francisco J. Abad [a], Kenia Martínez [a], Mª Ángeles Quiroga [c], Richard J. Haier [d]

[a] Universidad Autónoma de Madrid, Spain
[b] Fundación CIEN-Fundación Reina Sofía, Spain
[c] Universidad Complutense de Madrid, Spain
[d] University of California at Irvine, USA
[e] Universidad Pompeu Fabra, Barcelona, Spain
[f] Montreal Neurological Institute (MNI), Canada

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ABSTRACT

Evidence from neuroimaging studies suggests that intelligence differences may be supported by a parieto-frontal network. Research shows that this network is also relevant for cognitive functions such as working memory and attention. However, previous studies have not explicitly analyzed the commonality of brain areas between a broad array of intelligence factors and cognitive functions tested in the same sample. Here fluid, crystallized, and spatial intelligence, along with working memory, executive updating, attention, and processing speed were each measured by three diverse tests or tasks. These twenty-one measures were completed by a group of one hundred and four healthy young adults. Three cortical measures (cortical gray matter volume, cortical surface area, and cortical thickness) were regressed against psychological latent scores obtained from a confirmatory factor analysis for removing test and task specific variance. For cortical gray matter volume and cortical surface area, the main overlapping clusters were observed in the middle frontal gyrus and involved fluid intelligence and working memory. Crystallized intelligence showed an overlapping cluster with fluid intelligence and working memory in the middle frontal gyrus. The inferior frontal gyrus showed overlap for crystallized intelligence, spatial intelligence, attention, and processing speed. The fusiform gyrus in temporal cortex showed overlap for spatial intelligence and attention. Parietal and occipital areas did not show any overlap across intelligence and cognitive factors. Taken together, these findings underscore that structural features of gray matter in the frontal lobes support those aspects of intelligence related to basic cognitive processes.

Introduction

Evidence from neuroimaging studies suggests that intelligence differences among individuals may be supported by a parieto-frontal network (PFIT model; Jung and Haier, 2007) that also is related to basic cognitive processing. There is a large set of published articles analyzing the behavioral relationships between intelligence and cognitive measures (see Sternberg, 2000 for a summary). However, the number of studies addressing the simultaneous correlation among several diverse intelligence and cognitive constructs is much smaller (Ackerman et al., 2002; Colom et al., 2004, 2008; Krumm et al., 2009; Martínez et al., 2011; Oberauer et al., 2005). This state of affairs provides an uncertain general picture regarding their overlap. Thus, for instance, as noted by Nisbett et al. (2012) there are largely different estimations of the 'true' correlation between intelligence and working memory capacity. Variations from study to study might be attributed to the specific measures administered, the way latent factors are defined, the nature of the samples, and so forth. The heterogeneity of findings and lack of consensus may be behind the relative neglect of this particular topic in the review of intelligence research in the last 10 years recently published by Deary (2012).

In the comprehensive behavioral study reported by Martínez et al. (2011) fluid intelligence, short-term memory, executive updating, and working memory were hardly distinguished at the latent variable level. In this study, twenty-four measures were analyzed tapping eight intelligence and cognitive factors (three measures for each factor): fluid, crystallized, and spatial intelligence, along with short-term memory, working memory capacity, executive updating, attention, and processing speed. Their main findings supported the view that fluid intelligence can be largely identified with basic short-term storage processes, namely, encoding, maintenance, and retrieval. This was in keeping with neuroimaging evidence suggesting

* Corresponding author at: Universidad Autónoma de Madrid, 28049 Madrid, Spain.
E-mail address: roberto.colom@uam.es (R. Colom).

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that fluid intelligence shares relevant brain structural (Colom et al., 2007) and functional (Gray et al., 2003) correlates with working memory capacity (Halford et al., 2007). This was also seen as possibly consistent with behavioral studies suggesting that intensive training on executive updating, using the n-back task, might improve fluid intelligence, even when cognitive requirements of these two constructs are superficially very different (Jaeggi et al., 2008, 2010, 2011).

There are few neuroimaging studies comprehensively measuring several intelligence and cognitive factors with the same sample of participants, as discussed by Haier et al. (2009). They suggested several guidelines for a proper estimation of the constructs of interest with respect to the neuroimaging analysis of intelligence. The key one was the use of three or more varied measures to define each group factor. This guideline should be generalized to other cognitive variables as well, as underscored by Colom and Thompson (2011).

Here we apply this basic guideline for defining several relevant intelligence and cognitive factors: fluid intelligence, crystallized intelligence, spatial intelligence, working memory capacity, executive updating, attention, and processing speed. The behavioral relationships among the considered constructs were analyzed by confirmatory factor analysis for obtaining scores, as representative as possible, removing variance specific to each test and task. These psychological scores were then submitted to different imaging analysis protocols quantifying cortical gray matter volume (GMV), cortical surface area (CSA), and cortical thickness (CT).

These brain indices are considered separately because previous research shows that they should be distinguished. Sanabria-Diaz et al. (2010) have demonstrated that CSA and CT quantify largely distinguishable brain properties. These indices are supported by substantially different cellular mechanisms of different genetic origins (Panizzon et al., 2009; Winkler et al., 2010). Individual differences in CSA depend upon the number of columns, while individual differences in CT depend on the number of cells within a given column. Cortical gray matter volume (GMV) is a composite of CSA and CT, but individual differences in cortical GMV show a greater association with differences in CSA than with differences in CT. Furthermore, Winkler et al. (2010) found that variability in CSA is higher than in CT, and Winkler et al. (2012) note that CSA shows a great variation among species, but this is not the case for CT, meaning that evolution operates with more intensity over the former index. Finally, Sanabria-Diaz et al. (2010) suggest that CSA (and therefore GMV) may be better than CT for capturing the balance between local specialization and global integration in the brain. Following these evidences, we expect more visible findings for GMV and CSA than for CT when considering individual differences in higher cognitive processes.

Although the approach of the present study is mainly exploratory, taking into account previous evidence both at the behavioral and neuroimaging levels (Colom et al., 2007; Gray et al., 2003) it is predicted that (a) fluid intelligence and working memory will show the clearest overlap in the brain, and (b) this overlap will be focused in basic frontal (approx BA 9/10, 45, 46, and 47) and parietal (approx. BAs 7 and 39/40) areas (Colom et al., 2009; Jung and Haier, 2007).

Method

Participants and neuroimaging data

The sample comprised 104 young adults (59 females and 45 males) with a mean age of 19.9 (SD = 1.6). Exclusion criteria included neurological or psychiatric illness, considering a history of serious head injury and substance abuse. Informed consent was obtained following the Helsinki guidelines.

MRIs were obtained with a 3 T scanner (GEHC Waukesha, WI, 3 T Excite HDX) 8-channels coil. 3D: FSPGR with IR preparation pulse (TR 5.7 ms, TE 2.4 ms TI 750 ms, flip angle 12). Sag acquisition 0.8 mm thickness, full brain coverage (220 slices), matrix 266 × 266 FOV 24 (isotropic voxels 0.7 cm^3).[1]

Psychological measures

Twenty-one cognitive tests and tasks were administered for measuring the psychological constructs of interests. Fluid-abstract intelligence (Gf) assesses the complexity level that subjects can handle in situations for which previous knowledge is not relevant, whereas crystallized-verbal intelligence (Gc) relies in the ability to cope with academic types of skills and knowledge, such as reading or math (Cattell, 1971). Spatial intelligence (Gv) implicates the construction, temporary retention, and manipulation of mental images (Lohman, 2000). Working memory can be defined as the ability for the simultaneous storage and processing of varied amounts of information (Colom et al., 2006). Executive control implicates the ability for regulating mental processes. Inhibition, shifting and updating are key components of this type of control (Friedman et al., 2006). Attention is a broad cognitive function for focusing available mental resources (Baddeley, 2002). Here we consider the control of automatic responses (inhibition). Finally, processing speed is usually measured by reaction time tasks (Sheppard and Vernon, 2008), so simple verification tasks are administered in the present study. All these constructs were estimated by three different measures for obtaining theoretically representative scores using a latent variable approach.

Abstract-fluid intelligence (Gf) was measured by the Raven Advanced Progressive Matrices Test (RAPM) (Raven et al., 2004), the abstract reasoning subtests from the Differential Aptitude Test (DAT-AR) battery (Bennett et al., 1990), and the inductive reasoning subtests from the Primary Mental Abilities (PMA-R) battery (Thurstone, 1938). The RAPM comprises a matrix figure with three rows and three columns. Among eight possible alternatives the one completing the 3 × 3 matrix figure must be chosen. The screening version comprising odd items only was administered (max. score = 18). DAT-AR is a series test based on abstract figures. Successive figures follow a given rule, so the one continuing the series must be chosen from several alternatives. The screening version comprising odd items only was administered (max. score = 20). PMA-R comprises letters' series items. The rule (or rules) underlying a given sequence must be extracted for selecting the correct alternative (max. score = 30).

Verbal-crystallized intelligence (Gc) was measured by the verbal and numerical reasoning subtests from the DAT (VR and NR), along with the vocabulary subtest from the PMA (V). DAT-VR is based on sentences stated like an analogy. The first and last words from the sentence are missing, and a pair of words completing the sentence must be selected. The screening version comprising odd items only was administered (max. score = 20). PMA-V is a synonym test based on the meaning of words that must be evaluated against a given model word (max. score = 50). DAT-NR consists of quantitative reasoning problems. The screening version comprising odd items only was administered (max. score = 20).

Spatial intelligence (Gv) was measured by the spatial relations subtest from the DAT (SR), the spatial rotation subtest from the PMA (S), and the rotation of solid figures test (Yela, 1969). Items from the rotation of solid figures test are based on a 3D model figure and several 3D rotated alternatives (max. score = 21). PMA-S includes a model figure and six alternatives, some of which are simply rotated versions of the model figure, whereas the remaining figures

[1] We have previously published some reports using this sample (Bruner et al., 2010, 2011, 2012; Burgaleta et al., 2012; Colom et al., 2009; Martin-Loeches and Bruner, in press). However, only Colom et al. (2009) applied a VBM approach and the analyses were focused on *g* and residualized Gc (crystallized-verbal intelligence) and Gv (spatial intelligence). Further, (a) only sex was controlled for, (b) the cerebellum was removed from the brain images, and (c) a *p* level of 0.005 uncorrected was employed.