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Common and unique neuro-functional basis of induction, visualization, and spatial relationships as cognitive components of fluid intelligence

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ABSTRACT

Neuroimaging research of fluid intelligence (Gf) has mainly focused on the neural basis of abilities explaining performance on cognitive tasks. However, the neuro-functional basis of clearly defined theoretical cognitive components underlying Gf remains unclear. Induction, visualization, and spatial relationships have the highest relevance for Gf (Carroll, 1993). Here we report a functional magnetic resonance imaging (fMRI) study exploring the neural correlates of these abilities characterized by their unidimensionality and matched for task-difficulty, as evidenced by a psychometric calibration study. Twenty-two healthy young adult females, recruited from a large sample of 300 participants, with either below- or above-average Gf abilities underwent fMRI scanning during Gf task performance. The results reveal that these tasks activate a shared frontoparietal network. Specific activations were also observed, in particular for induction and visualization. The key findings suggest that Gf comprises distinguishable cognitive abilities, but the Gf construct is associated with a common network.

Introduction

Fluid intelligence (Gf) involves thinking logically, understanding relationships between stimuli, and solving problems in novel situations (Cattell, 1963, 1971). Gf is central for the general factor of intelligence (*g*) quantifying the positive correlation among widely diverse cognitive tests and tasks (Carroll, 1993; Cattell, 1963; Deary et al., 2010; Jensen, 1980, 1998; Spearman, 1927). Specifically, performance on Gf tasks predicts a large variety of cognitive activities, from laboratory tasks to everyday situations (Deary et al., 2007; Gottfredson, 1997; Gray and Thompson, 2004; Hunt, 2011).

From a psychometric perspective, human cognitive abilities are identified at different levels within a stratified structure. One of the most influential frameworks in this regard is Carroll's three strata theory based on the factor analysis of hundreds of cognitive datasets collected in different countries. The most specific factors are located at the lowest stratum (narrow cognitive abilities), whereas the highest stratum represents the general factor *g* (Carroll, 1993). Gf belongs to the second stratum and it is the closest broad ability to *g* (Carroll, 1993). Some narrow cognitive abilities on the lowest stratum have high loadings on Gf but also some uniqueness. These abilities are induction, visualization, spatial relationships, and quantitative reasoning.

Regarding the neurobiological basis of Gf, functional neuroimaging research has attempted to clarify the neural processes supporting this factor as a function of individual differences and task complexity (Perfetti et al., 2009). In contrast with neuroimaging research focusing on the association between specific cognitive functions and specific cerebral structures, these studies mainly elucidated the neural basis of general cognitive abilities explaining performance on multiple cognitive tasks (Deary et al., 2010; Duncan, 2010). The main results generally show activation related to Gf abilities in a frontoparietal network comprised by medial and lateral prefrontal cortices, anterior cingulate cortex, anterior insula, and posterior parietal cortex (Duncan et al., 2000; Gray et al., 2003; Jung and Haier, 2007; Lee et al., 2006; Perfetti et al., 2009; Prabhakaran et al., 1997). These results also received some support from lesion and morphometric studies (Barbey et al., 2012; Duncan et al., 1995; Glascher et al., 2009, 2010; Jung and Haier, 2007; Roca et al., 2010; Woolgar et al., 2010). It has been proposed that this network supports broad common cognitive functions (Colom et al., 2006; Duncan, 2010; Gray and Thompson, 2004). The integrity of this common network could be critical for performance on a wide variety of

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cognitive tasks and, hence, related to the positive correlation among cognitive tasks already mentioned (Colom et al., 2006; Deary et al., 2010; Duncan, 2010; Glascher et al., 2010).

Despite the fine grained analysis of the psychometric structure of human intelligence, the association between Gf and specific cognitive abilities remains unclear from a neuroscientific perspective, mostly because psychometric and neuroscientific methodologies are rarely integrated (Colom and Thompson, 2011; Colom et al., 2010). Cognitive tasks draw on common and unique abilities (Colom et al., 2009; Haier et al., 2009). The available psychometric evidence suggests that a general factor accounts for a large proportion of the variance (50% or more), whereas specific cognitive abilities show a substantial amount (20 to 50%) of unique variance (Deary et al., 2010). The latter comprises error and task-specific variance. This suggests that variance in task performance can be explained by specific neural processes involved in the task. However, studies investigating biological associations with intelligence are rarely conducted using psychometrically validated factors representing Gf specific cognitive domains. Thus, the role for the specific Gf components within the network remains to be explored within an integrative framework.

Here we report an fMRI study investigating how Gf is represented in the human brain taking into account Gf specific cognitive factors according to Carroll's framework (Carroll, 1993). In particular, we wonder whether distinct, but psychometrically unidimensional, Gf abilities evoke activation in specific brain regions and whether individual differences in Gf can be related to differential activation in specific brain regions.

Furthermore, it has been proposed that intelligence differences are related to neural network integrity and organization (Barbey et al., 2012; Colom et al., 2010; Glascher et al., 2010; Langer et al., 2011; Li et al., 2009; van den Heuvel et al., 2009), rather than activation foci in discrete brain regions. Therefore, we also investigate whether Gf differences involve connections with ability-specific brain regions or whether differences in connectivity are confined to ability-nonspecific brain regions.

For this purpose, induction, visualization, and spatial relationship tasks were administered to healthy participants with either low or high Gf ability while undergoing fMRI scanning. Gf tasks were psychometrically validated in an extensive calibration study showing that they significantly loaded on Gf and were characterized by unidimensionality, though represented distinguishable cognitive factors. This procedure allowed an accurate matching among tasks with respect to their difficulty and stimuli characteristics. Analysis of the blood oxygen level dependent (BOLD) signal concerned task-related neural activation patterns, as well as intrinsic functional connectivity patterns between task-related activation clusters, as an indicator of network integrity in terms of brain long range communication.

Material and methods

Participants

Twenty-two female university students (age range: 20–24) participated in the present study and were selected from a large database of volunteers ($N=300$) that completed a well-known fluid intelligence test, namely, the Raven's Advanced Progressive Matrices (APM; Raven, 1965). Selection of participants was based on APM scores. These scores were transformed to z-scores. Twelve participants were characterized by above average Gf abilities (HGF; z-score between 1.0 and 2.0) and 10 participants were characterized by below average Gf abilities (LGF; z-score between −1.0 and −2.0). All participants were healthy, right-handed (Edinburgh Handedness Inventory score > 0.85) and had normal or corrected-to-normal vision capabilities. Written informed consent was obtained from all participants after full explanation of the study's procedure, in line with the Declaration of Helsinki. The experimental protocol was approved by the local institutional ethics committee. Participants were paid 25 € for their participation in the fMRI experiment.

Calibration study of the Gf test

A new fluid intelligence test (FIT) was created by one of us (R.R.) at the Laboratory of Psychometrics, Department of Neuroscience and Imaging, G. d'Annunzio University, Chieti-Pescara, Italy. The test comprised an item bank of 220 items. Following Carroll's framework (1993) four subtests were included: induction (IN), quantitative reasoning (QR), visualization (VZ), and spatial relationships (SR). Induction is defined by the ability to inspect a class of stimuli and then to infer/induce/deduce a common characteristic underlying these materials. Visualization involves manipulating or transforming the image of spatial patterns into other visual arrangements. Spatial relationships is based on the ability to perceive spatial patterns or to maintain orientation with respect to objects in space. Finally, quantitative reasoning is defined by the ability to reason deductively or inductively based on mathematical properties and relations (Carroll, 1993).

The FIT was validated by a calibration study in large samples of participants. Regarding its psychometric properties, the FIT showed a proper internal consistency and a good construct validity. Two parallel forms of the FIT correlated significantly with APM total score ($r_{FIT\text{-}1;APM}=0.55$; $r_{FIT\text{-}2;APM}=0.72$), and were made up of items with a mean difficulty level, good discrimination and an acceptable level of guessing. Furthermore, unidimensionality and local independence assumptions were met for both forms. Unidimensionality means that the test measures a single trait. Local independence implicates that all items are correlated with one another, because they are different measures of the same latent trait. If we maintain the latent trait constant, all items will be independent, given that their relationship is only determined by that specific latent trait.

A more detailed description of the calibration study and its results is available in the Supplementary material.

Stimuli

75 visual items were extracted from the FIT subtests for the fMRI study; 25 items from each subtest represented a specific first-order Gf factor: induction, visualization, and spatial relationships. These factors were marked by identical visual characteristics and type of task. The quantitative reasoning factor from the original test was not included in the present study, because of the very different nature of the stimuli. The items selected across the different factors were matched for difficulty according to Item Response Theory (IRT; Bock, 1997; Embreston and Reise, 2000) parameters obtained by the calibration study (Table 1; see also Supplementary material).

All test items of the induction, visualization, and spatial relationship factors consisted of black and white line drawings. Every item in the test has four response categories indicated by a letter (a, b, c and d), among which participants must choose the correct answer. The problem of each item involves finding the figure representing the most suitable answer to the specific question preceding each item by multiple choice. Questions were visually presented on the screen and could be, for example, "Which figure completes the

Table 1
Difficulty of the selected items for the different Gf conditions used for the fMRI experiment according to IRT parameter a (difficulty; mean ± standard deviation).

Induction	Visualization	Spatial relationships
−0.82 ± 0.95	−0.82 ± 0.93	−0.82 ± 0.96