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Neural substrates of the Topology Test to measure fluid reasoning: An fMRI study ☆

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Abstract

In our prior study the negative correlation between Topology, a behavioral measure of fluid reasoning, and adult age diminished with the increase in the level of expertise in a cognitively-demanding domain of expertise in the game of GO. The present fMRI study was designed to investigate neural substrates of Topology. The modified topology sub-test of Cattell's Culture Fair Intelligence Tests was used as cognitive stimuli. The results indicated that higher-order cognition of Topology was supported by neural networks in: (1) the parietal cortex which is involved in activating possible responses based on learned stimulus-response associations, and (2) the prefrontal cortex that is recruited when there is a need to generate and evaluate hypotheses, and select between competing responses. Our results were consistent with previous neuroimaging studies of reasoning using Raven's Progressive Matrices that revealed the engagement of the prefrontal cortex and the parietal cortex in inductive reasoning. The future need was discussed to systematically examine neural networks supporting Topology over the course of expertise development and adult development in order to specify unique aspects of fluid reasoning that support high levels of cognitive behaviors of Topology.

Keywords: Fluid reasoning; fMRI; Individual differences; Expertise

Carroll (1993) has done a tour-de-force summary of over 400 factor analytic studies and showed that more than 40 primary abilities and eight second-order factors of the primary abilities can reliably describe important features of human intelligence. A factor that signifies the second-order factors is fluid reasoning (Gf), the ability that is closely aligned with a concept that Spearman described as *g*. Gf is the measurable outcome of incidental learning and neurophysiological health, and represents capacities of inductive reasoning for abstracting, identifying relationships, comprehending implications, and drawing inferences in a novel context.

To date, some brain-imaging studies have examined neural networks that support cognitive behaviors of Gf

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reasoning (Duncan et al., 2000; Goel & Dolan, 2004; Gray, Chabris, & Braver, 2003; Gray & Thompson, 2004; Haier, White, & Alkire, 2003; Houde & Tzourio-Mazoyer, 2003; Lee et al., 2006; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997). Generally, the findings from neuroimaging studies have suggested activations of prefrontal and posterior parietal cortices during Gf reasoning tasks (Houde & Tzourio-Mazoyer, 2003; Prabhakaran et al., 1997). For instance, in an attempt to determine neural substrates of fluid reasoning, Prabhakaran, Smith, Desmond, Glover and Gabrieli (1997) compared two different forms of Raven's Progressive Matrices Tests (i.e., analytic and figural/visuospatial reasoning). Although figural/visuospatial problems required minimal analytic reasoning, analytic problems required examinees to carefully analyze the stimuli and find rules that determined the progression of adjacent entries of the matrices. Their functional Magnetic Resonance Imaging (fMRI) data demonstrated that analytic reasoning was associated with right frontal and parietal regions that were also activated during figural/visuospatial problems, left-hemisphere systems for domain-specific verbal and object working memory, left-hemisphere areas for induction of visuospatial relations, and frontal areas closely related to goal management, strategy shifting, planning, or executive control processes of working memory.

Lee et al. (2006) also demonstrated that the prefrontal cortex (PFC), a key brain region that was suspected to support reasoning and novel problem solving, indeed was the neurological basis of Gf. Individuals with higher Gf, as measured with Raven's Progressive Matrices, were more accurate on a very demanding working memory task, and showed greater neural activity, particularly in lateral PFC and parietal cortex, during the most demanding tasks. Colom, Jung, and Haier (2006) reported that most of the correlation between general factor of intelligence (*g*) and gray and white matter volumes were found in the frontal lobe. Specifically, their results indicated such correlations in frontal Brodmann area (BAs) 47, 9, 10, 11, and 46; temporal BA 36 (fusiform gyrus), occipital BA 18 (lingual gyrus), and BA 13 (sub-lobar insula). In studies that focused on individual differences in neural networks in the brain, posterior information processing areas were more strongly activated among individuals with higher intelligence scores than those with low intelligence scores even while completing non-reasoning tasks (Haier et al., 2003), the correlations between IQ and gray matter were strongest in frontal and parietal lobes (BA 8, 9, 39, 40) in men and in frontal lobe (BA10) and Broca's area in women (Haier, Jung, Yeo, Head, & Alkire, 2005), boys and girls differed in developmental processes in intelligence (Schmithorst & Holland, 2006), and brain structure related to *g* were not invariant across young and older adults (Colom et al., 2006; Haier, Jung, Yeo, Head, & Alkire, 2004).

Despite some individual differences noted above, generally studies have shown dominant engagement of prefrontal cortex in human inductive reasoning (Duncan et al., 2000; Goel & Dolan, 2004) and additional recruitment of posterior areas (Haier et al., 1988). Indeed, in a review of 37 imaging studies related to intelligence, Jung and Haier (2007) found remarkable consistency in the findings from the studies, despite a variety of approaches employed by the studies. Based on this analysis, Jung and Haier posited the Parieto-Frontal Integration Theory (P-FIT) of intelligence, stipulating that: (1) intelligence is related to a brain network that primarily involves frontal and the parietal lobes, (2) levels of intelligence are the reflection of how efficient the frontal–parietal networks process information, and (3) individual differences in intelligence stem from individual differences in the connections in these networks, or the effectiveness of pathways in the brain along which information travels.

A potential issue in extant fMRI studies of Gf reasoning, however, is that they have predominantly used Raven's Progressive Matrices (Raven, Court, & Raven, 1977) as cognitive stimuli. As summarized in the argument by Snow, Kyllonen, and Marshalek (1984), the Raven's Progressive Matrices Test was often regarded as the ideal measure of Gf that requires verbal, spatial, and mathematical problem solving abilities. However, Raven's Progressive Matrices is not the only representative psychometric measure of Gf reasoning abilities. Indeed, Gf abilities have been widely measured in tasks involving syllogisms and concept formation (Fisk & Sharp, 2002; McGrew, Werder, & Woodcock, 1991), in reasoning with metaphors and analogies (Salthouse, 1987; Salthouse, Kausler, & Saults, 1990), with measures of comprehending series, as in letter series, figural series, and number series (Horn, 1975, 1991; Noll & Horn, 1997; Salthouse et al., 1990), and with measures of mental rotation, figural relations, matrices, and topology (Cattell, 1979; Horn, 1977; McArdle, Hamagami, Meredith, & Broadway, 2000). No single measure of Gf can provide a comprehensive assessment that encompasses all aspects of complex Gf abilities.

Cattell designed the Culture Fair Intelligence Tests to measure Gf reasoning abilities that do not hinge on acculturation experiences (Cattell & Cattell, 1973). The composite score from the tests' four subscales, including (1) Series, (2) Classifications, (3) Matrices, and (4) Conditions, loaded .48 on the Gf factor, and −.08 on the Gc