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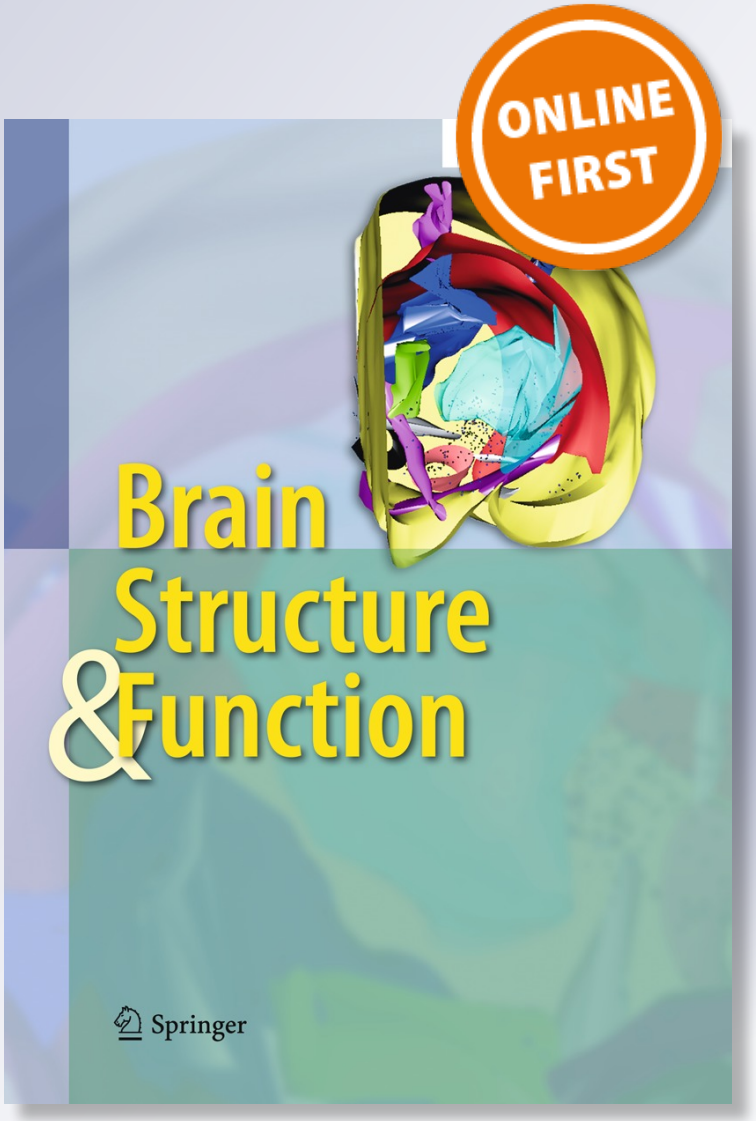

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ORIGINAL ARTICLE

Architecture of fluid intelligence and working memory revealed by lesion mapping

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Abstract Although cognitive neuroscience has made valuable progress in understanding the role of the prefrontal cortex in human intelligence, the functional networks that support adaptive behavior and novel problem solving remain to be well characterized. Here, we studied 158 human brain lesion patients to investigate the cognitive and neural foundations of key competencies for fluid intelligence and working memory. We administered a battery of neuropsychological tests, including the Wechsler Adult Intelligence Scale (WAIS) and the N-Back task. Latent variable modeling was applied to obtain error-free scores of fluid intelligence and working memory, followed by voxel-based lesion-symptom mapping to elucidate their neural substrates. The observed latent variable modeling and lesion results support an integrative framework for understanding the architecture of fluid intelligence and working memory and make specific recommendations for the interpretation and application of the WAIS and N-Back task to the study of fluid intelligence in health and disease.

Keywords Fluid intelligence · Working memory · Prefrontal cortex · Voxel-based lesion-symptom mapping

Introduction

The search for general principles that govern human intelligence began over a century ago and was led by the pioneering work of Charles Spearman (Spearman 1904), who discovered that individual patterns of performance across a broad range of cognitive tests are positively correlated. This observation led Spearman (Spearman 1928) to propose that a general factor (*g*) accounts for performance across the spectrum of cognitive activities—spanning perception, attention, memory, language, and thought. In factor analytic studies, the best tests of *g* involve fluid intelligence or novel problem solving (Cattell 1971; Carroll

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1993). High performance in such tests is predictive of broad success in many different kinds of cognitive activity, from educational and work achievements to social well being and mental health (Jensen 1998).

It remains an open question what cognitive and neural systems are causally related to fluid intelligence (*Gf*). This intellectual ability enables people to solve novel problems independently of previously acquired knowledge and is critical for adaptive behavior and goal-directed decision making. There are several accepted measures of *Gf*, such as the Raven Progressive Matrices Test or the Culture Fair Intelligence Test (Jensen 1998; Roca et al. 2010). Beyond specific measures, *Gf* estimates can also be achieved by assembling several non-verbal or abstract tests. This approach is often desirable as it avoids contaminating *Gf* estimates with task-specific variance. From this perspective, subtests of the perceptual organization factor of the Wechsler Adult Intelligence test (WAIS) are considered reasonable approximations to fluid intelligence (Duncan et al. 1995; Roca et al. 2010).

A growing body of evidence further indicates that intellectual ability is closely related to working memory performance. At the behavioral level, there are several comprehensive studies showing that they are (almost) isomorphic. Kyllonen and Christal (1990) found structural coefficients greater than 0.80 between intellectual ability and working memory. Ackerman and colleagues (Ackerman et al. 2002) report a structural coefficient of 0.70 between general intelligence (*g*) and working memory. Süb and colleagues (Suss et al. 2002) found correlations larger than 0.60. Across three separate large-scale studies conducted in two different countries, Colom et al. (2004) found a mean structural coefficient of 0.96 between *g* and working memory. Martinez et al. (2011) found that *Gf* and working memory cannot be distinguished at the latent variable level. Studies showing that working memory training might improve fluid intelligence (Jaeggi et al. 2008, 2010, 2011), along with neuroimaging reports showing structural (Colom et al. 2007) and functional (Gray et al. 2003) overlaps between working memory and intelligence, are consistent with the emerging hypothesis that these psychological factors are closely related.

Indeed, functional brain imaging evidence indicates that general intelligence (*g*) and working memory engage a common neural network (Nyberg et al. 2003). This network incorporates the lateral prefrontal cortex (PFC) in and around the inferior frontal sulcus and the anterior insula/frontal operculum, the dorsal anterior cingulate/pre-supplementary motor area, a small region of the anterior frontal cortex, and the intraparietal sulcus. In putative monkey homologs of frontal and parietal regions, including posterolateral PFC, neural activity is shaped strongly by cognitive context, adapting to code many different kinds of task-relevant information. Broad activity in many different kinds of behavior is a requirement for neural systems linked to *g* (Duncan 2010), and functional brain imaging studies show strong fronto-parietal activity during fluid intelligence tests (Duncan 2001).

Although our understanding of the architecture of fluid intelligence and working memory has been enriched by insights from functional neuroimaging studies, they cannot establish whether the observed frontal and parietal regions are causally necessary for these processes. For this purpose lesion data are critical (Glascher et al. 2010; Woolgar et al. 2010; Barbey et al. 2012a). Patients with focal brain lesions provide a rare opportunity to study the mechanisms underlying fluid intelligence and working memory, supporting the investigation of lesion-deficit associations that elucidate the necessity of specific brain structures. Of the patient studies that have examined the neural bases of fluid intelligence (Basso et al. 1973; Black 1976; Eslinger and Damasio 1985; Shallice and Burgess 1991; Bechara et al. 1994; Duncan et al. 1995; Burgess and Shallice 1996; Duncan et al. 1996; Isingrini and Vazou 1997; Parkin and Java 1999; Blair and Cipolotti 2000; Kane and Engle 2002; Bugg et al. 2006; Glascher et al. 2009, 2010; Roca et al. 2010) and working memory (D'Esposito and Postle 1999; Muller et al. 2002; Baldo and Dronkers 2006; D'Esposito et al. 2006; Volle et al. 2008; Tsuchida and Fellows 2009), all share one or more of the following features: diffuse (rather than focal) brain lesions, lack of comparison subjects carefully matched for pre- and post-injury performance measures, and exclusive use of fluid intelligence or working memory tests. As a consequence, there has been no comprehensive evaluation of fluid intelligence and working memory in a relatively large sample of patients with focal brain damage, and across a broad range of tasks and stimulus material.

The main goal of the present investigation is to provide an empirical basis for developing a theory that specifies the cognitive and neural architecture of fluid intelligence and working memory. Here we administered standard neuropsychological tests of fluid intelligence and working memory, selecting tasks that are designed to assess each function and examining the extent of unity or diversity of these processes at the latent variable level (i.e., examining what is shared among the exemplar tasks for each executive function). Therefore, we statistically ''extract'' what is common among the tasks selected to tap a putative executive factor and use error-free scores derived from the latent variable factors to examine how different executive functions relate to one another. This latent variable approach has a number of important advantages over more typical approaches; foremost among them being an emphasis on latent (rather than manifest) variables which serve to minimize task impurity.

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We studied a large sample of 158 human patients with focal brain injuries to investigate the relationship between fluid intelligence and working memory task performance. We report a latent analysis of these factors from a battery of neuropsychological tests and apply voxel-based lesion-symptom mapping to elucidate their neural substrates (Bates et al. 2003).

Materials and methods

Participant data

Participants were drawn from the Phase 3 Vietnam Head Injury Study (VHIS) registry, which includes American male veterans who all suffered brain damage from penetrating head injuries in the Vietnam War ($n = 158$). All subjects gave informed written consent. Phase 3 testing occurred between April 2003 and November 2006. Demographic and background data for the VHIS are reported in Supplemental Table 1 (see also Koenigs et al. 2009; Raymont et al. 2010; Barbey et al. 2011, 2012a). No effects on test performance were observed in the VHIS sample on the basis of demographic variables (e.g., age, years of education, lesion size).

Lesion analysis

CT data were acquired during the Phase 3 testing period. Axial CT scans without contrast were acquired at Bethesda Naval Hospital on a GE Medical Systems Light Speed Plus CT scanner in helical mode (150 slices per subject, field of view covering head only). Images were reconstructed with an in-plane voxel size of 0.4 × 0.4 mm, overlapping slice thickness of 2.5 mm, and a 1 mm slice interval. Lesion location and volume were determined from CT images using the Analysis of Brain Lesion software (Makale et al. 2002; Solomon et al. 2007) contained in MEDx v3.44 (Medical Numerics) with enhancements to support the Automated Anatomical Labeling atlas (Tzourio-Mazoyer et al. 2002). Lesion volume was calculated by manual tracing of the lesion in all relevant slices of the CT image then summing the traced areas and multiplying by slice thickness. A trained neuropsychiatrist performed the manual tracing, which was then reviewed by an observer who was blind to the results of the neuropsychological testing. As part of this process, the CT image of each subject's brain was spatially normalized to a CT template brain image. This template was created by spatial normalization of a neurologically healthy individual's CT brain scan to MNI space using the Automated Image Registration program (Woods et al. 1993). For each subject, a lesion mask image in MNI space was saved for voxel-based lesion-symptom mapping (Bates et al. 2003). This method applies a t test to compare, for each voxel, scores from patients with a lesion at that voxel contrasted against those without a lesion at that voxel. Thus, this method compares the performance of patients with damage to a given voxel with that of patients who also have brain damage but not including that specific voxel. It is important to keep in mind that this method does not compare lesion patients to neurologically healthy participants. The reported findings were thresholded using a False Discovery Rate correction of $q < 0.05$. To ensure sufficient statistical power for detecting a lesion-deficit correlation, our analysis included only voxels for which four or more patients had a lesion. The lesion overlap map for the entire VHIS patient sample is illustrated in Supplemental Fig. 2 ($n = 158$).

Neuropsychological tests

We administered subtests of the Wechsler adult intelligence scale, third edition (WAIS, Wechsler 1997) and an experimental test of working memory, the N-Back task (Cohen et al. 1997), to investigate the neural substrates underlying (1) process-specific operations (monitoring and manipulation) and (2) content-specific representations (verbal/numeric and spatial) in working memory. Monitoring refers to the process of deliberately attending to information in working memory and is measured by active retention tasks (the N-Back task). The one-, two- and three-back conditions of the N-Back task support an investigation of the neural mechanisms underlying working memory with increasing computational complexity. Manipulation refers to the rearrangement and transformation of representations in working memory and is measured by tasks that draw upon executive control processes (e.g., arithmetic and letter-number sequencing task). Fluid intelligence (G*f*) scores were obtained from three key perceptual organization subtests of the WAIS-III; namely, matrix reasoning, block design, and picture completion. Johnson and Bouchard (2005) identified verbal, perceptual, and image rotation global intelligence factors, noting a near perfect correlation between the general factor of intelligence (*g*) and a perceptual factor (0.99) underlying fluid intelligence (G*f*). Supplementary Table 2 summarizes the administered neuropsychological tests (for further detail concerning their standardization, reliability, and validity, see Cohen et al. 1997; Wechsler 1997).

Confirmatory factor analysis

The following measurement model was tested (Supplemental Fig. 1): (1) *Gf* was assessed by matrix reasoning, block design, and picture completion; (2) working memory monitoring operations were investigated by the one-, two-,

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and three-back conditions; (3) working memory manipulation processes were measured by arithmetic and letter-number sequencing; (4) verbal/numeric working memory was measured by digit span forward/backward; and, finally, (5) spatial working memory comprised measures for spatial span forward/backward.

This five factor model produced very good fit indices: $\chi^2 = 62.57$, degrees of freedom (DF) = 44, $\chi^2/\text{DF} = 1.4$, RMSEA = 0.052, CFI = 0.97. There are several noteworthy results: (a) all regression weights for the considered measures show relatively high values on their respective latent factors; (b) monitoring, verbal/numeric, and spatial working memory regression weights are largely consistent with the cognitive complexity that can be predicted from their nature: three-back shows a value of 0.85, two-back shows a value of 0.75, and one-back shows a value of 0.45 (also, the backward versions of the working memory tasks show greater values than the forward versions); (c) all correlations among factors are statistically significant ($p < 0.000$) except that between *Gf* and working memory monitoring operations ($r = -0.16$, $p = 0.103$); (d) the correlation between *Gf* and the working memory manipulation factor for verbal/numeric and spatial representations is highly similar (from 0.60 to 0.67).

Having demonstrated the appropriateness of this measurement model, we computed composite scores for the five constructs of interest (Colom et al. 2009; Haier et al. 2009; Karama et al. 2011). Standardized scores (z) were computed for the twelve measures. Afterwards, average z scores were calculated for *Gf* and all working memory factors. Correlation values among these average z scores were consistent with those identified in the measurement model. These average z scores were submitted to lesion analyses. The derived z scores for each subject were correlated to regional gray and white matter determined by voxel-based lesion-symptom mapping (Bates et al. 2003). This method compares, for every voxel, scores from patients with a lesion at that voxel contrasted against those without a lesion at that voxel (applying a false discovery rate correction of $q < 0.05$).

Similarity analysis

In order to quantify the degree of similarity of the thresholded group-level lesion-symptom maps, the Dice coefficient was computed for each pair of images. This method has been used in fMRI analyses to measure the degree of similarity between super-threshold cluster maps (Rombouts et al. 1997; Bennett and Miller 2010). Specifically, thresholded maps were binarized (i.e., where the value "1" indicates a super-threshold voxel) and masked to include only those voxels inside the standardized brain volume. Similarity between maps was calculated with the following formula:

$$s = \frac{2|V_1 \cap V_2|}{|V_1| + |V_2|},$$

where V_i is the masked, thresholded binary map corresponding to group-map i. This formula is equivalent to calculating the number of overlapping (or shared) super-threshold voxels, divided by the average total super-threshold voxels of the images. The Dice coefficient is easy to interpret because the maximum value of 1 indicates perfect similarity while the minimum value of 0 indicates no similarity.

Results

Fluid intelligence

Gf was associated with a broadly distributed network of brain regions primarily within the right hemisphere (Fig. 1; illustration of gray and white matter results). Significant effects encompassed locations for: (1) language processing (e.g., Broca's area and right superior temporal gyrus); (2) spatial processing (e.g., right inferior and superior parietal cortex); (3) motor processing (e.g., right somatosensory and primary motor cortex); and (4) working memory (e.g., right dorsolateral PFC, right inferior and superior parietal cortex, and right superior temporal gyrus); in addition to expected locations of major white matter fiber tracts, including (5) the anterior and dorsal bundle of the superior longitudinal/arcuate fasciculus connecting temporal, parietal, and inferior frontal regions; (6) the superior fronto-occipital fasciculus connecting dorsolateral PFC and the frontal pole with the superior parietal lobule; and (7) the uncinate fasciculus, which connects anterior temporal cortex and amygdala with orbitofrontal and frontopolar regions. This pattern of findings suggests that *Gf* reflects the ability to effectively integrate verbal, spatial, motor, and executive processes via a circumscribed set of cortical connections in the right hemisphere.

Process-specific mechanisms: monitoring representations in working memory

Impairments in N-Back task performance were associated with damage to a distinct network of regions within right ventrolateral PFC (BA 47), right inferior parietal cortex (BA 40), and right middle temporal gyrus (BA 22) (Fig. 2; regions highlighted in yellow). Although this network is largely distinct from the system underlying fluid intelligence, a region of overlap within the right inferior parietal cortex (BA 40) was observed (Fig. 2).

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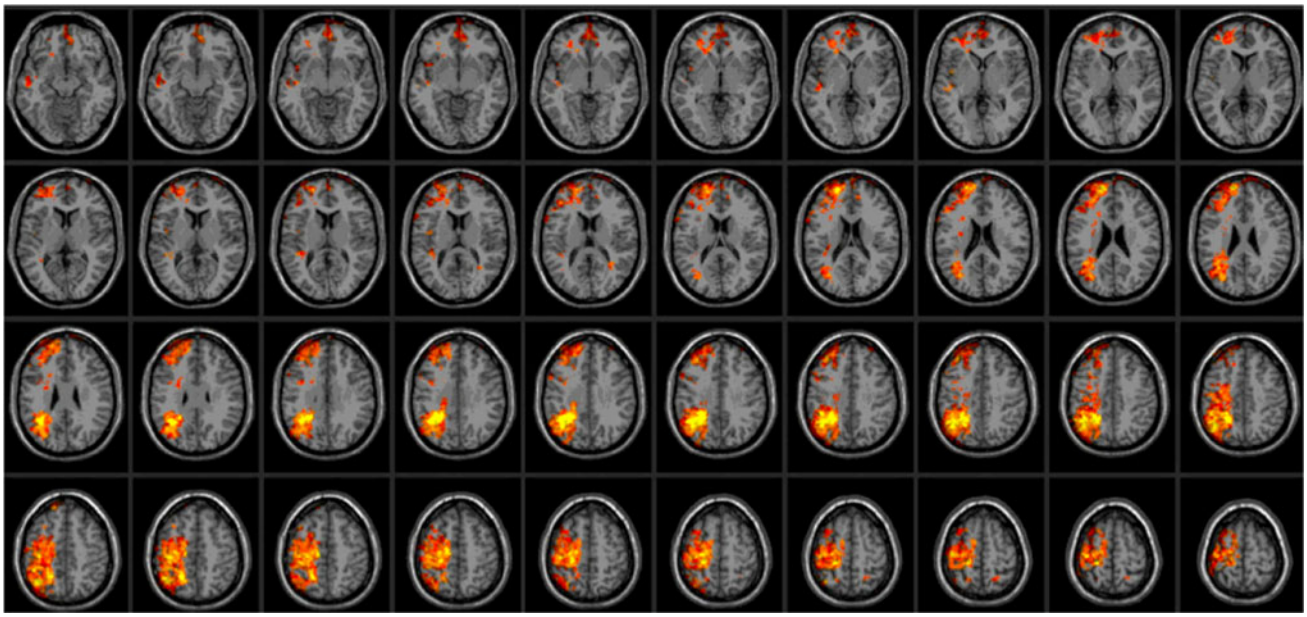

Fig. 1 Lesion mapping results for general fluid intelligence ($n = 158$). The statistical map is thresholded at 5 % false discovery rate. In each axial slice, the right hemisphere is on the reader's *left*

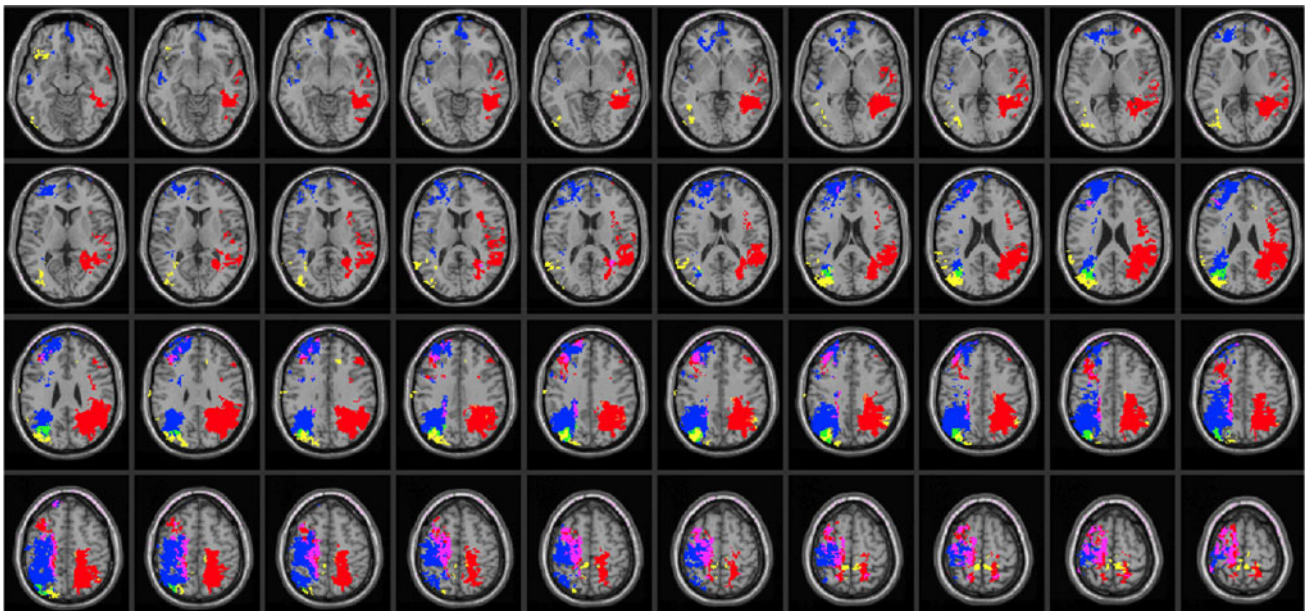

Fig. 2 Lesion overlap map illustrating common and distinctive brain regions for fluid intelligence (*blue*) and process-specific working memory mechanisms for monitoring (*yellow*) and manipulating (*red*) information ($n = 158$). Overlap between fluid intelligence and monitoring operations for working memory is illustrated in *green*. Overlap between fluid intelligence and manipulating operations for working memory is illustrated in *pink*. Overlap between monitoring and manipulating processes in working memory is illustrated in *orange*. Overlap between all conditions is illustrated in *white*. The statistical map is thresholded at 5 % false discovery rate. In each axial slice, the right hemisphere is on the reader's *left*

Process-specific mechanisms: manipulating representations in working memory

Figure 2 illustrates that the process of manipulating information in working memory primarily engaged a left lateralized network (highlighted in red), including left angular gyrus (BA 39), left superior parietal cortex (BA 7) and left superior temporal gyrus (BA 41/42/22). In addition, brain areas implicated in fluid intelligence were recruited, including right dorsolateral PFC (BA 9) and right

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superior fronto-occipital fasciculus connecting dorsolateral PFC and the frontal pole with the superior parietal lobule (Fig. 2; regions highlighted in red).

Content-specific mechanisms: verbal/numeric working memory

Figure 3 shows that impairments in verbal/numeric working memory were associated with damage primarily within the left hemisphere (highlighted in yellow), including left angular gyrus (BA 39), left superior parietal cortex (BA 7) and left superior temporal gyrus (BA 41/42/22). In addition, deficits in verbal/numeric working memory were associated with damage to regions implicated in fluid intelligence, including right dorsolateral PFC (BA 9), right superior fronto-occipital fasciculus, and right superior parietal cortex (BA 7) (Fig. 3; regions highlighted in yellow).

Content-specific mechanisms: spatial working memory

Figure 3 illustrates that spatial working memory impairments were associated with selective damage to brain regions also implicated in fluid intelligence (highlighted in red), including right dorsolateral PFC (BA 9), right superior parietal cortex (BA 7), and the right superior fronto-occipital fasciculus.

Relationship between fluid intelligence and working memory

The observed pattern of findings indicates that fluid intelligence (*Gf*) shares anatomical substrates with both process- and content-specific mechanisms for working memory. In particular, we found that *Gf* depends on a right lateralized network of frontal and parietal brain regions that are also critically important for the manipulation of verbal and spatial representations in working memory (Figs. 2, 3). The results further indicate that *Gf* and working memory may differ in important respects, as operations for monitoring items in working memory (measured by the N-Back task) largely engaged distinct neural substrates (Fig. 2). This result is also consistent with the observed pattern of correlations derived from the confirmatory factor analysis, which demonstrates low correlations between fluid intelligence and working memory monitoring factors (Supplemental Fig. 1). Indeed, the correspondence between the confirmatory factor analysis and voxel-based lesion-symptom mapping results is striking, as factors that are highly correlated appear to also engage similar neural machinery (Fig. 4).

The apparent correspondence between the confirmatory factor analysis and the voxel-based lesion-symptom mapping was formally assessed in two steps. First, the Dice coefficient between each pair of lesion-symptom maps was

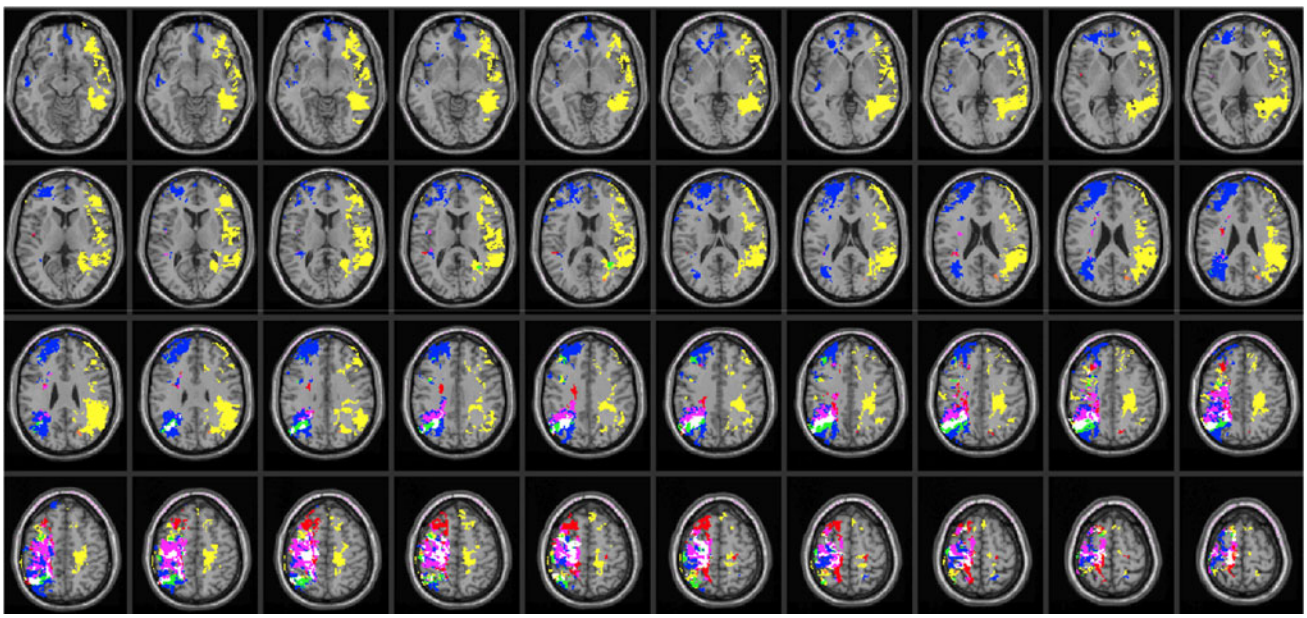

Fig. 3 Lesion overlap map illustrating common and distinctive brain regions for fluid intelligence (*blue*) and content-specific mechanisms for representing verbal/numeric (*yellow*), and spatial (*red*) information in working memory ($n = 158$). Overlap between fluid intelligence and verbal/numeric working memory is illustrated in *green*. Overlap between fluid intelligence and spatial working memory is illustrated in *pink*. Overlap between verbal/numeric and spatial working memory is illustrated in *orange*. Overlap between all conditions is illustrated in *white*. The statistical map is thresholded at 5 % false discovery rate. In each axial slice, the right hemisphere is on the reader's *left*

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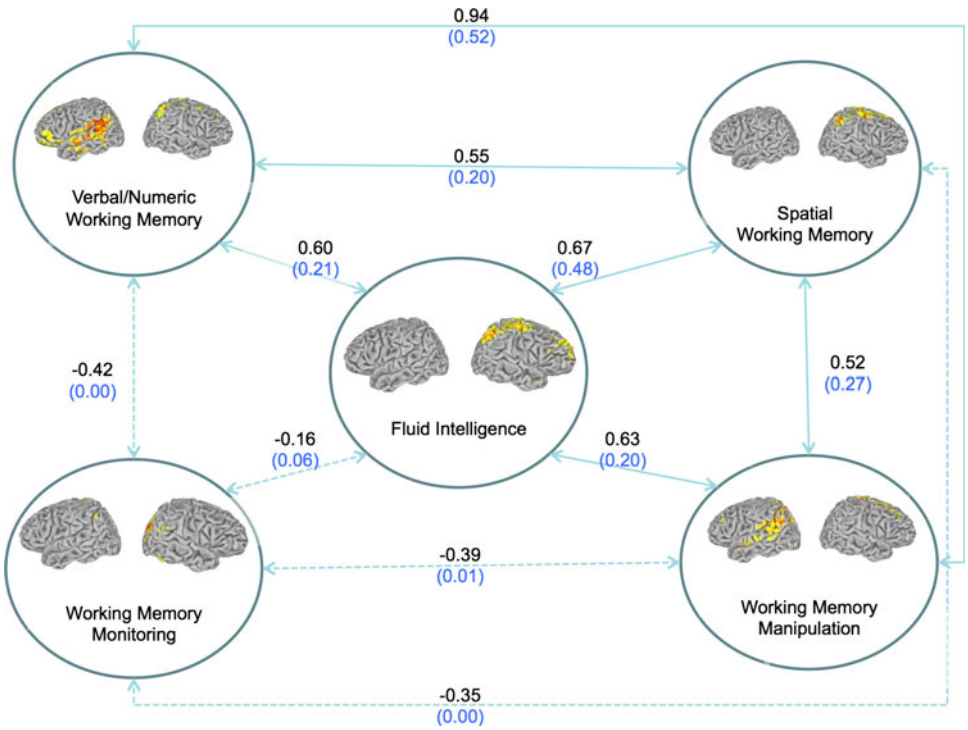

Fig. 4 Summary of lesion mapping and structural equation modeling results ($n = 158$). Factor loadings among latent variables of fluid intelligence and working memory are illustrated in *black*. Dice coefficients of the spatial similarity among brain regions for each latent variable are illustrated in *blue*. The statistical map is thresholded at 5 % false discovery rate. In each map of the cortical surface, the left hemisphere is on the reader's *left*

computed. The results of this analysis are included in Fig. 4. Note that the Dice coefficient is favorable in the present application for two reasons: first, as mentioned above, the value of the statistic is constrained between 0 (i.e., no similarity) and 1 (i.e., perfect similarity) and so it is easily interpretable; second, our analyses are concerned with the distribution of compromised voxels significantly related to cognitive performance; hence, our intention to compare the distribution of significant voxels in the lesion-symptom maps for each factor of interest. Second, we computed the correlation between the structural equation modeling results and the observed Dice coefficient for each pair of factors. The results revealed a highly significant positive relationship [$r(8) = 0.89$, $p < 0.001$], suggesting factors that are highly correlated in the factor analysis appear to also share a high degree of similarity (i.e., more overlapping significant voxels) in lesion-symptom maps (Fig. 4).

Discussion

In this study, we investigated the neural architecture of fluid intelligence and its relation to key competencies for working memory. We administered standard neuropsychological tests of fluid intelligence and working memory to 158 patients with focal brain injuries and applied voxel-based lesion-symptom mapping to investigate their neural substrates. A methodological strength of this approach is that it enables lesion-symptom mapping of broad brain networks within a large sample of lesion patients. A potential limitation of this approach is that it evaluates the influence of damage to a specific voxel in the context of damage to other regions, (which may or may not contribute to the observed pattern of findings). We believe voxel-based lesion-symptom mapping should therefore be applied in conjunction with studies that employ the classic lesion method, comparing lesion patients to neurologically healthy participants (Barbey et al. 2011, 2012b), and complementing functional neuroimaging studies of the intact brain.

Our results indicate that the neural substrates of fluid intelligence are remarkably circumscribed, concentrated in white matter fiber tracts that connect frontal and parietal cortices. As Fig. 1 illustrates, impairments in fluid intelligence were associated with damage to the superior longitudinal/arcuate fasciculus, consistent with research implicating these white matter sectors in general intelligence and executive function (Glascher et al. 2010; Barbey et al. 2012a).

We further observed that the neural substrates of fluid intelligence comprise a narrow subset of regions associated with performance on individual WAIS subtests. The largest overlap between WAIS subtests and fluid intelligence was found for tests that (1) require the manipulation of cognitive representations (mental arithmetic and letter-number sequencing; Fig. 2), and (2) operate on verbal/numeric (digit span) or spatial representations (spatial span; Fig. 3).

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Collectively, these measures assess the ability to manipulate verbal/numeric and spatial representation in working memory and are associated with a right lateralized fronto-parietal network. This pattern of findings suggests that fluid intelligence and working memory centrally depend on mechanisms for the manipulation and control of cognitive representations, and that the communication between areas associated with these capacities is of critical importance.

The observed findings contribute to a growing body of neuropsychological patient evidence indicating that damage to a distributed network of frontal and parietal regions is associated with impaired performance on tests of general intelligence (Jung and Haier 2007; Colom et al. 2009; Glascher et al. 2009; Glascher et al. 2010). General intelligence, or psychometric g, is defined as the aspect of cognition whose variance is shared maximally across a wide variety of more specialized tasks, such as reasoning, spatial ability, and memory. A recent study by Barbey and colleagues (Barbey et al. 2012a) applied voxel-based lesion-symptom mapping to elucidate the neural substrates of psychometric *g*, reporting a left lateralized fronto-parietal network that largely mirrors the observed pattern of findings for fluid intelligence in the right hemisphere. Taken together, these finding indicate that the fronto-parietal network is central to human intelligence and may be lateralized according to whether mechanisms for general (left hemisphere) or fluid (right hemisphere) intelligence are engaged.

The fronto-parietal network identified by the present analysis includes lateral frontopolar cortex, anterior PFC, dorsolateral PFC, anterior cingulate/medial PFC, and the inferior and superior parietal lobe (Fig. 2). This constellation of regions is commonly engaged by tasks that require executive control processes (Ramnani and Owen 2004). The fronto-parietal network is recruited by paradigms that elicit controlled processing related to the simultaneous consideration of multiple interdependent contingencies (Kroger et al. 2002), conflicting stimulus–response mappings (Crone et al. 2006), and integrating working memory with attentional resource allocation (Koechlin et al. 1999). In addition, many of the regions in the fronto-parietal network show sustained activity over the duration of a task block (Dosenbach et al. 2006), supporting the maintenance and integration of items for goal-directed behavior. The involvement of this network in the present study therefore suggests that fluid intelligence fundamentally depends on mechanisms for the manipulation and control of cognitive representations (Botvinick et al. 2001; Miller and Cohen 2001; Duncan 2010).

The conclusion that fluid intelligence and working memory engage a distributed fronto-parietal network is also consistent with the emerging empirical case in support of a strong dependency between fluid intelligence and working memory (Kyllonen and Christal 1990; Colom et al. 2004, 2005; Martinez et al. 2011) and research indicating that working memory training may improve fluid intelligence (Jaeggi et al. 2008, 2010; Jaeggi et al. 2011). The reported findings contribute to this research program by further demonstrating that fluid intelligence engages a right lateralized neural system and shares common anatomical substrates with mechanisms for specific working memory operations.

The importance of the fronto-parietal network in fluid intelligence is supported by recent evidence to suggest that this network represents a central feature in the evolution of the human brain. Previous cytoarchitectonic and histological studies have shown that the PFC, particularly Brodmann area 10, is greatly expanded in both absolute size and percentage of whole brain volume in humans relative to macaques and apes (Semendeferi et al. 2001). Van Essen and Dierker (2007) applied anatomical MRI to generate a map of estimated cortical expansion between macaque and human, identifying the anterior lateral PFC and anterior inferior parietal lobule as regions of greatest cortical expansion in humans. Collectively, these studies indicate that the human fronto-parietal network may be especially important in the evolution of the human brain and the development of key competencies for fluid intelligence and working memory.

From a clinical perspective, understanding fluid intelligence deficits in patients with fronto-parietal damage may greatly facilitate the design of appropriate assessment tools and rehabilitation strategies, with potential improvement in patients' cognitive abilities and daily living. The findings reported here identify specific tests of the WAIS that may be targeted in clinical investigations to assess the functioning of the fronto-parietal network, particularly, measures of fluid intelligence (picture completion, block design, and matrix reasoning) and working memory (arithmetic and letter-number sequencing). The observed findings elucidate brain structures that are engaged by both fluid intelligence and working memory, as well as identifying some regions involved in one that may not be recruited by the other. These findings support predictions about the nature and significance of cognitive impairments that may result from damage to specific brain regions (Fig. 4). Our results also have important implications for the interpretation of standard neuropsychological tests of intelligence, such as the Wechsler Adult Intelligence Scale, which classify the administered tests of working memory as measures of crystallized intelligence that are distinct from G*f* (Wechsler 1997). The observed findings instead suggest that specific competencies for working memory are critically important for fluid intelligence, which demonstrate common patterns of behavioral performance and engage similar neural mechanisms (Fig. 4).

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We emphasize in closing that the abilities measured by the WAIS and N-Back Task do not provide a comprehensive assessment of all human cognitive abilities. There are other aspects of human cognitive ability in addition to those capacities measured by the WAIS and N-Back that contribute to mental life, notably those related to social and emotional functioning (Barbey et al. 2009, 2012c). Understanding the neural architecture of fluid intelligence and working memory will ultimately require a broader assessment that examines the functional organization of cognitive, social, and affective systems, and their interactive role in high-level processes. The reported finding contributes to this emerging research program by elucidating the role of the fronto-parietal network in fluid intelligence and working memory, demonstrating that this system provides an integrative architecture for key competencies underlying adaptive behavior and novel problem solving.

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References

Ackerman PL, Beier ME, Boyle MO (2002) Individual differences in working memory within a nomological network of cognitive and perceptual speed abilities. J Exp Psychol Gen 131:567–589

Baldo JV, Dronkers NF (2006) The role of inferior parietal and inferior frontal cortex in working memory. Neuropsychology 20:529–538

Barbey AK, Krueger F, Grafman J (2009) An evolutionarily adaptive neural architecture for social reasoning. Trends Neurosci 32:603–610

Barbey AK, Koenigs M, Grafman J (2011) Orbitofrontal contributions to human working memory. Cereb Cortex 21:789–795

Barbey AK, Colom R, Solomon J, Krueger F, Forbes C, Grafman J (2012a) An integrative architecture for general intelligence and executive function revealed by lesion mapping. Brain 135:1154–1164

Barbey AK, Koenigs M, Grafman J (2012b) Dorsolateral prefrontal contributions to human working memory. Cortex (epub ahead of print)

Barbey AK, Colom R, Grafman J (2012c) Distributed neural system for emotional intelligence revealed by lesion mapping. Soc Cogn Affect Neurosci (Epub ahead of print)

Basso A, De Renzi E, Faglioni P, Scotti G, Spinnler H (1973) Neuropsychological evidence for the existence of cerebral areas critical to the performance of intelligence tasks. Brain 96:715–728

Bates E, Wilson SM, Saygin AP, Dick F, Sereno MI, Knight RT, Dronkers NF (2003) Voxel-based lesion-symptom mapping. Nat Neurosci 6:448–450

Bechara A, Damasio AR, Damasio H, Anderson SW (1994) Insensitivity to future consequences following damage to human prefrontal cortex. Cognition 50:7–15

Bennett CM, Miller MB (2010) How reliable are the results from functional magnetic resonance imaging? Ann N Y Acad Sci 1191:133–155

Black FW (1976) Cognitive deficits in patients with unilateral war-related frontal lobe lesions. J Clin Psychol 32:366–372

Blair RJ, Cipolotti L (2000) Impaired social response reversal. A case of 'acquired sociopathy'. Brain 123(Pt 6):1122–1141

Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD (2001) Conflict monitoring and cognitive control. Psychol Rev 108:624–652

Bugg JM, Zook NA, Delosh EL, Davalos DB, Davis HP (2006) Age differences in fluid intelligence: contributions of general slowing and frontal decline. Brain Cogn 62:9–16

Burgess PW, Shallice T (1996) Response suppression, initiation and strategy use following frontal lobe lesions. Neuropsychologia 34:263–272

Carroll JB (1993) Human cognitive abilities: a survey of factor-analytic studies. Cambridge University Press, Cambridge

Cattell RB (1971) Abilities: their structure, growth, and action. Houghton Mifflin, Boston

Cohen JD, Perlstein WM, Braver TS, Nystrom LE, Noll DC, Jonides J, Smith EE (1997) Temporal dynamics of brain activation during a working memory task. Nature 386:604–608

Colom R, Rebollo I, Palacios A, Juan-Espinosa M, Kyllonen PC (2004) Working memory is (almost) perfectly predicted by g. Intelligence 32:277–296

Colom R, Abad FJ, Rebollo I, Shih PC (2005) Memory span and general intelligence: a latent-variable approach. Intelligence 33:623–642

Colom R, Jung RE, Haier RJ (2007) General intelligence and memory span: evidence for a common neuroanatomic framework. Cogn Neuropsychol 24:867–878

Colom R, Haier RJ, Head K, Alvarez-Linera J, Quiroga MA, Shih PC, Jung RE (2009) Gray matter correlates of fluid, crystallized, and spatial intelligence: testing the P-FIT model. Intelligence 37:124–135

Crone EA, Wendelken C, Donohue SE, Bunge SA (2006) Neural evidence for dissociable components of task-switching. Cereb Cortex 16:475–486

D'esposito M, Postle BR (1999) The dependence of span and delayed-response performance on prefrontal cortex. Neuropsychologia 37:1303–1315

D'esposito M, Cooney JW, Gazzaley A, Gibbs SE, Postle BR (2006) Is the prefrontal cortex necessary for delay task performance? Evidence from lesion and FMRI data. J Int Neuropsychol Soc 12:248–260

Dosenbach NU, Visscher KM, Palmer ED, Miezin FM, Wenger KK, Kang HC, Burgund ED, Grimes AL, Schlaggar BL, Petersen SE (2006) A core system for the implementation of task sets. Neuron 50:799–812

Duncan J (2001) An adaptive coding model of neural function in prefrontal cortex. Nat Rev Neurosci 2:820–829

Duncan J (2010) The multiple-demand (MD) system of the primate brain: mental programs for intelligent behaviour. Trends Cogn Sci 14:172–179

Duncan J, Burgess P, Emslie H (1995) Fluid intelligence after frontal lobe lesions. Neuropsychologia 33:261–268

Duncan J, Emslie H, Williams P, Johnson R, Freer C (1996) Intelligence and the frontal lobe: the organization of goal-directed behavior. Cogn Psychol 30:257–303

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Eslinger PJ, Damasio AR (1985) Severe disturbance of higher cognition after bilateral frontal lobe ablation: patient EVR. Neurology 35:1731–1741

Glascher J, Tranel D, Paul LK, Rudrauf D, Rorden C, Hornaday A, Grabowski T, Damasio H, Adolphs R (2009) Lesion mapping of cognitive abilities linked to intelligence. Neuron 61:681–691

Glascher J, Rudrauf D, Colom R, Paul LK, Tranel D, Damasio H, Adolphs R (2010) Distributed neural system for general intelligence revealed by lesion mapping. Proc Natl Acad Sci USA 107:4705–4709

Gray JR, Chabris CF, Braver TS (2003) Neural mechanisms of general fluid intelligence. Nat Neurosci 6:316–322

Haier RJ, Colom R, Schroeder DH, Condon CA, Tang C, Eaves E, Head K (2009) Gray matter and intelligence factors: is there a neurology? Intelligence 37:136–144

Isingrini M, Vazou F (1997) Relation between fluid intelligence and frontal lobe functioning in older adults. Int J Aging Hum Dev 45:99–109

Jaeggi SM, Buschkuehl M, Jonides J, Perrig WJ (2008) Improving fluid intelligence with training on working memory. Proc Natl Acad Sci USA 105:6829–6833

Jaeggi SM, Studer-Luethi B, Buschkuehl M, Su YF, Jonides J, Perrig WJ (2010) The relationship between n-back performance and matrix reasoning—implications for training and transfer. Intelligence 38:625–635

Jaeggi SM, Buschkuehl M, Jonides J, Shah P (2011) Short- and long-term benefits of cognitive training. Proc Natl Acad Sci USA 108:10081–10086

Jensen AR (1998) The g factor: the science of mental ability. Praeger, Westport, Conn

Johnson W, Bouchard TJ (2005) The structure of human intelligence: it is verbal, perceptual, and image rotation (VPR), not fluid and crystallized. Intelligence 33:393–416

Jung RE, Haier RJ (2007) The Parieto-Frontal Integration Theory (P-FIT) of intelligence: converging neuroimaging evidence. Behav Brain Sci 30:135–154 (discussion 154–187)

Kane MJ, Engle RW (2002) The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: an individual-differences perspective. Psychon Bull Rev 9:637–671

Karama S, Colom R, Johnson W, Deary IJ, Haier R, Waber DP, Lepage C, Ganjavi H, Jung R, Evans AC (2011) Cortical thickness correlates of specific cognitive performance accounted for by the general factor of intelligence in healthy children aged 6 to 18. Neuroimage 55:1443–1453

Koechlin E, Basso G, Pietrini P, Panzer S, Grafman J (1999) The role of the anterior prefrontal cortex in human cognition. Nature 399:148–151

Koenigs M, Barbey AK, Postle BR, Grafman J (2009) Superior parietal cortex is critical for the manipulation of information in working memory. J Neurosci 29:14980–14986

Kroger JK, Sabb FW, Fales CL, Bookheimer SY, Cohen MS, Holyoak KJ (2002) Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: a parametric study of relational complexity. Cereb Cortex 12:477–485

Kyllonen PC, Christal RE (1990) Reasoning ability is (little more than) working-memory capacity. Intelligence 14:389–433

Makale M, Solomon J, Patronas NJ, Danek A, Butman JA, Grafman J (2002) Quantification of brain lesions using interactive automated software. Behav Res Methods Instr Comput 34:6–18

Martinez K, Burgaleta M, Roman FJ, Escorial S, Shih PC, Quiroga MA, Colom R (2011) Can fluid intelligence be reduced to 'simple' short-term storage? Intelligence 39:473–480

Miller EK, Cohen JD (2001) An integrative theory of prefrontal cortex function. Annu Rev Neurosci 24:167–202

Muller NG, Machado L, Knight RT (2002) Contributions of subregions of the prefrontal cortex to working memory: evidence from brain lesions in humans. J Cogn Neurosci 14:673–686

Nyberg L, Marklund P, Persson J, Cabeza R, Forkstam C, Petersson KM, Ingvar M (2003) Common prefrontal activations during working memory, episodic memory, and semantic memory. Neuropsychologia 41:371–377

Parkin AJ, Java RI (1999) Deterioration of frontal lobe function in normal aging: influences of fluid intelligence versus perceptual speed. Neuropsychology 13:539–545

Ramnani N, Owen AM (2004) Anterior prefrontal cortex: insights into function from anatomy and neuroimaging. Nat Rev Neurosci 5:184–194

Raymont V, Salazar AM, Lipsky R, Goldman D, Tasick G, Grafman J (2010) Correlates of posttraumatic epilepsy 35 years following combat brain injury. Neurology 75:224–229

Roca M, Parr A, Thompson R, Woolgar A, Torralva T, Antoun N, Manes F, Duncan J (2010) Executive function and fluid intelligence after frontal lobe lesions. Brain 133:234–247

Rombouts SA, Barkhof F, Hoogenraad FG, Sprenger M, Valk J, Scheltens P (1997) Test-retest analysis with functional MR of the activated area in the human visual cortex. AJNR Am J Neuroradiol 18:1317–1322

Semendeferi K, Armstrong E, Schleicher A, Zilles K, Van Hoesen GW (2001) Prefrontal cortex in humans and apes: a comparative study of area 10. Am J Phys Anthropol 114:224–241

Shallice T, Burgess PW (1991) Deficits in strategy application following frontal lobe damage in man. Brain 114(Pt 2):727–741

Solomon J, Raymont V, Braun A, Butman JA, Grafman J (2007) User-friendly software for the analysis of brain lesions (ABLe). Comput Methods Progr Biomed 86:245–254

Spearman C (1904) "General intelligence" objectively determined and measured. Am J Psychol 15:201–292

Spearman C (1928) The abilities of man. Science 68:38

Suss HM, Oberauer K, Wittmann WW, Wilhelm O, Schulze R (2002) Working-memory capacity explains reasoning ability—and a little bit more. Intelligence 30:261–288

Tsuchida A, Fellows LK (2009) Lesion evidence that two distinct regions within prefrontal cortex are critical for n-back performance in humans. J Cogn Neurosci 21:2263–2275

Tzourio-Mazoyer N, Landeau B, Papathanassiou D, Crivello F, Etard O, Delcroix N, Mazoyer B, Joliot M (2002) Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. Neuroimage 15:273–289

Van Essen DC, Dierker DL (2007) Surface-based and probabilistic atlases of primate cerebral cortex. Neuron 56:209–225

Volle E, Kinkingnehun S, Pochon JB, Mondon K, Thiebaut De Schotten M, Seassau M, Duffau H, Samson Y, Dubois B, Levy R (2008) The functional architecture of the left posterior and lateral prefrontal cortex in humans. Cerebral Cortex 18:2460–2469

Wechsler D (1997) Wechsler adult intelligence test administration and scoring manual. The Psychology Corporation, San Antonio

Woods RP, Mazziotta JC, Cherry SR (1993) MRI-PET registration with automated algorithm. J Comput Assist Tomogr 17:536–546

Woolgar A, Parr A, Cusack R, Thompson R, Nimmo-Smith I, Torralva T, Roca M, Antoun N, Manes F, Duncan J (2010) Fluid intelligence loss linked to restricted regions of damage within frontal and parietal cortex. Proc Natl Acad Sci USA 107: 14899–14902