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Architecture of cognitive flexibility revealed by lesion mapping

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Abstract

Neuroscience has made remarkable progress in understanding the architecture of human intelligence, identifying a distributed network of brain structures that support goal-directed, intelligent behavior. However, the neural foundations of cognitive flexibility and adaptive aspects of intellectual function remain to be well characterized. Here, we report a human lesion study (n = 149) that investigates the neural bases of key competencies of cognitive flexibility (i.e., mental flexibility and the fluent generation of new ideas) and systematically examine their contributions to a broad spectrum of cognitive and social processes, including psychometric intelligence (Wechsler Adult Intelligence Scale), emotional intelligence (Mayer, Salovey, Caruso Emotional Intelligence Test), and personality (Neuroticism–Extraversion–Openness Personality Inventory). Latent variable modeling was applied to obtain error-free indices of each factor, followed by voxel-based lesion-symptom mapping to elucidate their neural substrates. Regression analyses revealed that latent scores for psychometric intelligence reliably predict latent scores for cognitive flexibility (adjusted R^2 = 0.94). Lesion mapping results further indicated that these convergent processes depend on a shared network of frontal, temporal, and parietal regions, including white matter association tracts, which bind these areas into an integrated system. A targeted analysis of the unique variance explained by cognitive flexibility further revealed selective damage within the

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Appendix A. Supplementary data Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.neuroimage.2013.05.087.

right superior temporal gyrus, a region known to support insight and the recognition of novel semantic relations. The observed findings motivate an integrative framework for understanding the neural foundations of adaptive behavior, suggesting that core elements of cognitive flexibility emerge from a distributed network of brain regions that support specific competencies for human intelligence.

Keywords

Cognitive flexibility; Creativity; Latent variable modeling; Voxel-based lesion-symptom mapping

Introduction

Cognitive flexibility is a hallmark of human thought, enabling the ability to adapt in the face of environmental change and to generate new ideas that drive innovation and promote growth and discovery (Badre and Wagner, 2006; Hennessey and Amabile, 2010; Leuner and Gould, 2010; Stemme et al., 2005). Despite its central role in human mental life, remarkably little is known about the neural architecture of cognitive flexibility. At its core, cognitive flexibility reflects the adaptability of thought and behavior (Collins and Koechlin, 2012) and promotes the fluent generation of ideas (Costafreda et al., 2006; Gilhooly et al., 2007) and the recognition of novel semantic relations (Jung-Beeman et al., 2004). Cognitive flexibility can be expressed in multiple ways, ranging from the exhibition of genius in the arts and sciences to more mundane acts of adaptive problem solving in everyday life. Given the sheer breadth of conditions under which cognitive flexibility can manifest itself, there is a growing consensus among researchers that it is not a unitary construct (for reviews, see Barron and Harrington, 1981; Batey and Furnham, 2006; Runco, 2004). Rather, the necessary and sufficient conditions for adaptive behavior will vary as a function of task demands and their corresponding cognitive requirements. This perspective has motivated an increasing number of scientists to suggest that cognitive flexibility may depend on multiple information processing systems rather than originate from a unitary cognitive ‘module’ (Barron and Harrington, 1981; Batey and Furnham, 2006; Runco, 2004).

Parallel developments in cognitive neuroscience support this emergent perspective (for reviews, see Arden et al., 2010; Dietrich and Kanso, 2010). Dietrich and Kanso (2010) reviewed the neuroscience literature on cognitive flexibility and creative problem solving, examining studies that assessed: (1) divergent thinking (i.e., the ability to generate multiple solutions to open-ended problems); (2) cognition of art and music; and (3) insight (i.e., the recognition of novel semantic relations). Rather than identifying a unitary brain module that implements these aspects of adaptive behavior and creative problem solving, Dietrich and Kanso (2010) observed a highly variable pattern of brain activity; identifying, for example, only diffuse recruitment of the pre-frontal cortex across studies. Arden et al. (2010) reached a similar conclusion after reviewing the neuroscience literature on adaptive problem solving, having found no consistent pattern of brain activation across different experimental tasks and methods.

The inconsistent pattern of findings across studies raises fundamental questions about the usefulness of the theoretical constructs motivating the search for the neural bases of adaptive behavior and creative problem solving. Arden et al. (2010) point to the absence of task specificity as a major contributor to the heterogeneity of findings and suggest that a psychometric approach for characterizing the cognitive foundations of adaptive behavior is needed. This critique underscores the need for a coherent methodology to study specific and dissociable mental processes that underlie cognitive flexibility.

The lack of convergence within the literature on adaptive behavior and creative problem solving resonates to studies that have assessed the relationship between cognitive flexibility and other mental processes, such as general intelligence. Kim (2005), for example, conducted a meta-analysis of 21 studies of adaptive problem solving and intelligence, and found that performance across these domains was only weakly correlated (0.17; Kim, 2005). Nusbaum and Silvia (2011), however, challenged this conclusion, reporting a latent correlation of 0.42 between adaptive problem solving and fluid intelligence (Nusbaum and Silvia, 2011). In addition to advocating a psychometric approach, these authors emphasized the importance of investigating cognitive flexibility in a broader light, recommending that future research assess social and emotional processes that may play a central role in adaptive behavior.

Research on the neural bases of cognitive flexibility would therefore benefit from a more precise characterization of its cognitive foundations, applying a psychometric approach to identify key competencies of adaptive behavior and their relation to a broad spectrum of cognitive, emotional, and social processes. The application of lesion methods to map the information processing architecture of cognitive flexibility would further advance our understanding of the core mechanisms that give rise to adaptive behavior (Barbey et al., 2012c; Gläscher et al., 2010; Woolgar et al., 2010). Neuropsychological patients with focal brain lesions provide a valuable opportunity to study the neural mechanisms of cognitive flexibility, supporting the investigation of lesion-deficit associations that elucidate the necessity of specific brain structures. Although the neural foundations of cognitive flexibility remain to be assessed using lesion methods, the broader neuropsychological patient literature has provided significant insight into the neural bases of higher cognitive functions, such as general intelligence (Barbey et al., 2012c; Basso et al., 1973; Bechara et al., 1994; Black, 1976; Blair and Cipolotti, 2000; Bugg et al., 2006; Burgess and Shallice, 1996; Duncan et al., 1995; Eslinger and Damasio, 1985; Gläscher et al., 2009, 2010; Isingrini and Vazou, 1997; Kane and Engle, 2002; Parkin and Java, 1999; Roca et al., 2010; Shallice and Burgess, 1991) and working memory (Barbey et al., 2011; Barbey et al., 2012d; Baldo and Dronkers, 2006; D'Esposito and Postle, 1999; D'Esposito et al., 2006; Muller et al., 2002; Tsuchida and Fellows, 2009; Volle et al., 2008). These studies, however, 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, exclusive use of neuropsychological tests without an assessment of cognitive flexibility, and lack of latent variable modeling to derive error-free indices of the psychological constructs of interest. As a consequence, there has been no comprehensive evaluation of cognitive flexibility in a relatively large sample of patients with focal brain damage, and across a broad range of tasks and stimulus material.

Motivated by these considerations, we studied the neural bases of cognitive flexibility in a large sample of patients with focal brain injuries ($n = 149$). We applied latent variable modeling to characterize the psychometric properties of cognitive flexibility and we then assessed cognitive flexibility with respect to a broad spectrum of cognitive and social processes, including psychometric intelligence (Wechsler Adult Intelligence Scale), emotional intelligence (Mayer, Salovey, Caruso Emotional Intelligence Test), and personality traits (Neuroticism–Extroversion–Openness Personality Inventory). Finally, we applied voxel-based lesion-symptom mapping to elucidate the information processing architecture of cognitive flexibility, identifying core brain mechanisms that contribute to adaptive aspects of intellectual function.

Materials and methods

Participant data

Participants were drawn from the Phase 3 Vietnam Head Injury Study (VHIS) registry, which includes American male veterans who suffered brain damage from penetrating head injuries in the Vietnam War ($n = 149$). 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 Barbey et al., 2011, 2012c; Koenigs et al., 2009; Raymont et al., 2010). 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). It is important to note that all individuals in the VHIS sample are males and therefore conclusions drawn from this study are restricted to an adult male population.

Lesion analysis

CT data were acquired during the Phase 3 testing period. Axial CT scans without contrast were acquired at the 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 neurologist performed the manual tracing, which was then reviewed by an observer who was blind to the results of the neuro-psychological testing. Inter-rater reliability analysis demonstrated reliable consensus among neurologists (Barbey et al., 2011, 2012a, 2012b, 2012c, 2012d, 2013). 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 (Collins et al., 1994) 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. 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 only included voxels for which 4 or more patients had a lesion. The lesion overlap map for the entire VHIS patient sample is illustrated in Supplemental Fig. 1.

Psychological measures

We administered the Wechsler Adult Intelligence Scale, Third Edition (Wechsler, 1997) (WAIS-III), the Mayer, Salovey, Caruso Emotional Intelligence Test (Mayer et al., 2008) (MSCEIT), and the Neuroticism–Extraversion–Openness Personality Inventory (Costa and McCrae, 2000) (NEO-PI). At its core, cognitive flexibility reflects the adaptability of thought and behavior (Collins and Koechlin, 2012) and promotes the fluent generation of ideas (Costafreda et al., 2006; Gilhooly et al., 2007) and the recognition of novel semantic relations (Jung-Beeman et al., 2004). We therefore measured cognitive flexibility by administering tasks that examine: (1) the adaptability and flexibility of thought (category switching) (Collins and Koechlin, 2012); and (2) the fluent generation of ideas (letter fluency and category fluency) (Costafreda et al., 2006; Gilhooly et al., 2007). We applied latent variable modeling to derive a factor representative of these core aspects of cognitive flexibility and creative problem solving. We also obtained latent variables representative of

psychometric intelligence and emotional intelligence that were analyzed together with scores of basic personality traits (i.e., the big five). Latent factors for psychometric intelligence were derived from the WAIS-III, namely, verbal comprehension, fluid intelligence, working memory, and processing speed. The MSCEIT allowed the extraction of a general emotional intelligence index. Personality traits were measured by the NEO-PI, but treated separately from the cognitive measures. Supplemental Table 2 summarizes the employed measures of psychometric and emotional intelligence (for further detail concerning their standardization, reliability, and validity, see Mayer et al., 2008; Wechsler, 1997).

Latent variable modeling

The following measurement model was tested (Fig. 1): (1) cognitive flexibility was assessed by measures of mental flexibility (category switching; Collins and Koechlin, 2012) and the fluent generation of ideas (letter fluency, category fluency; Costafreda et al., 2006; Gilhooly et al., 2007); (2) verbal comprehension was assessed by the vocabulary, similarities, information, and comprehension subtests; (3) fluid intelligence was measured by block design, matrix reasoning, picture completion, picture arrangement, and object assembly; (4) working memory comprised measures of arithmetic, digit span, and letter–number sequencing; (5) processing speed was assessed by digit symbol coding and symbol search; and (6) emotional intelligence was measured by the full MSCEIT battery, including the faces, pictures, sensations, facilitation, blends, changes, emotional, and social subtests.

This six factor model produced reasonable fit indices: $\chi^2 = 443$, degrees of freedom (DF) = 260, $\chi^2/DF = 1.7$, RMSEA = 0.069. There are several noteworthy results: (a) all regression weights for the considered measures show relatively high values on their respective latent factors; (b) all correlations among factors are statistically significant ($p < 0.000$); (c) the correlations among cognitive flexibility, verbal comprehension, working memory, and processing speed were largely similar (from 0.62 to 0.77); and (d) the correlation between cognitive flexibility and emotional intelligence was also substantial (0.56). Having shown the appropriateness of this model, we computed latent scores for the constructs of interest (Colom et al., 2009; Haier et al., 2009; Karama et al., 2011).

Voxel-based lesion-symptom mapping

The obtained six latent factors 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 $q < 0.05$). Unlike functional neuroimaging studies, which rely on the metabolic demands of gray matter and provide a correlational association between brain regions and cognitive processes, voxel-based lesion-symptom mapping can identify regions playing a causal role over the constructs of interest by mapping where damage can interfere with performance (Barbey et al., 2012c; Gläscher et al., 2010; Woolgar et al., 2010).

Results

Cognitive flexibility

Cognitive flexibility was associated with a broadly distributed network of brain regions primarily within the left hemisphere (Fig. 1; regions highlighted in blue). Significant effects encompassed locations for: (1) language processing (e.g., Broca's area and left superior temporal gyrus); (2) spatial processing (e.g., left inferior and superior parietal cortex); (3) motor processing (e.g., left somatosensory and primary motor cortex); and (4) working memory (e.g., left dorsolateral PFC, left inferior and superior parietal cortex, and left

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 the dorsolateral PFC and the frontal pole with the superior parietal lobule; and (7) the uncinate fasciculus, which connects the anterior temporal cortex and amygdala with orbitofrontal and frontopolar regions. This pattern of findings suggests that cognitive flexibility reflects the ability to effectively integrate verbal, spatial, motor, and executive processes via a circumscribed set of cortical connections in the left hemisphere.

Stepwise regression

The latent factors for psychometric intelligence (verbal comprehension, fluid intelligence, working memory, and processing speed) and emotional intelligence along with the five personality traits were submitted to a stepwise regression analysis where cognitive flexibility was the dependent measure. The results showed that only psychometric factors reliably predict cognitive flexibility. The adjusted R^2 for working memory was 0.70. When processing speed was added, this value increased to 0.82, incorporating fluid intelligence raised this value to 0.89, and, finally, the adjusted R^2 reached a value of 0.94 when verbal comprehension was incorporated. Voxel-based lesion-symptom mapping results for these significant predictors of cognitive flexibility are illustrated in Figs. 2 and 3.

Language network

As Fig. 2 illustrates, cognitive flexibility shared neural substrates with verbal comprehension, engaging a left hemisphere language network (reviewed in Hickok and Poeppel, 2007; Fig. 2; regions highlighted in pink). This network is distributed throughout association areas in the left perisylvian cortex, comprising a ventral pathway that maps sound to meaning (language comprehension) and a dorsal pathway that maps sound to action (language production). The ventral pathway engaged the anterior middle temporal gyrus, posterior middle temporal gyrus, and middle posterior superior temporal sulcus. These regions are known to support the process of mapping sensory or phonological representations onto lexical/conceptual representations in language comprehension (Hickok and Poeppel, 2007). The dorsal pathway engaged the anterior and posterior insula and an area at the parietal–temporal boundary, which are known to contribute to mapping sensory or phonological representations onto articulatory motor representations in language production (Hickok and Poeppel, 2007). White matter fiber tracts of the perisylvian language network, including the arcuate and uncinate fasciculi, were also engaged by cognitive flexibility (Fig. 2; regions highlighted in pink). The anatomical extent of this network suggests that cognitive flexibility and language processes derive from the coordinated activity of several brain regions and largely engage a shared information processing architecture.

Fluid intelligence

Fluid intelligence engaged a right lateralized network that largely mirrored the left hemispheric network for cognitive flexibility, recruiting frontal and parietal regions that are commonly engaged by tasks that require executive control (Fig. 2; regions highlighted in yellow; for reviews, see Botvinick et al., 2004; Ramnani and Owen, 2004). The observed pattern of findings suggests that fluid intelligence and cognitive flexibility may critically differ in their hemispheric specialization. Although the specific brain regions are not shared, these aspects of intellectual function appear to depend on similar cognitive operations (based on latent variable modeling and stepwise regression findings; Fig. 1) and engage broadly homologous contralateral brain structures (based on voxel-based lesion-symptom mapping; Fig. 2).

Working memory

As illustrated in Fig. 3, cognitive flexibility shared neural substrates with working memory, engaging a broadly distributed network of frontal, temporal, and parietal regions of the left hemisphere (Fig. 3; regions highlighted in green). This network has been widely implicated in the maintenance, monitoring, and manipulation of representations in working memory (Owen et al., 2005; Wager and Smith, 2003) and provides evidence in this context for their central roles in cognitive flexibility.

Processing speed

Cognitive flexibility also shared neural substrates with processing speed, recruiting areas within the left ventromedial and dorsomedial prefrontal cortex that support visual–motor processing and coordination (Fig. 3; regions highlighted in pink; Sweet et al., 2005). The observed role of these regions in cognitive flexibility further suggests that its neural representation is multifaceted and engages mechanisms for basic aspects of cognitive processing (e.g., language, working memory, processing speed).

Residual cognitive flexibility scores

Finally, we analyzed the cognitive flexibility residual scores removing variance shared with its significant predictors (Fig. 4). This residual factor captures the unique variance associated with cognitive flexibility and supports an assessment of the core brain mechanisms underlying adaptive behavior. Impairments in cognitive flexibility (residual) were associated with selective damage to the right anterior superior temporal gyrus, a region known to support the formation of distant or novel semantic relations and to play a central role in insight problem solving (Jung-Beeman et al., 2004). This finding indicates that the right anterior superior temporal gyrus is critically important for cognitive flexibility and supports the role of this region in the formation of new semantic relations for adaptive problem solving.

Discussion

In this study, we investigated the neural bases of key competencies of cognitive flexibility and systematically examined their contributions to a broad spectrum of cognitive, social, and emotional processes, including psychometric intelligence, emotional intelligence, and personality. Using a relatively large sample of patients with focal brain injuries ($n = 149$), we report several main findings. First, a stepwise regression analysis demonstrated that latent scores for psychometric intelligence reliably predict latent scores for cognitive flexibility, providing evidence that adaptive behavior depends on key competencies for psychometric intelligence (i.e., verbal comprehension, working memory, fluid intelligence, and processing speed). Notably, this analysis did not support a significant association between cognitive flexibility and scores for social and emotional factors (i.e., personality traits and emotional intelligence). Second, voxel-based lesion-symptom mapping of latent scores for cognitive flexibility and its reliable predictors (i.e., psychometric intelligence factors) revealed that these convergent processes engage a shared network of frontal, temporal, and parietal regions. This analysis further demonstrated that cognitive flexibility shares neural mechanisms with specific competencies for psychometric intelligence, including verbal comprehension, working memory, and processing speed. Third, voxel-based lesion-symptom mapping of the unique variance explained by cognitive flexibility (while removing variance shared with its reliable predictors) revealed selective recruitment of the right anterior superior temporal gyrus, a region known to support the recognition of novel semantic relations and to play a central role in insight problem solving (Jung-Beeman et al., 2004).

Taken together, these finding contribute to a cognitive neuroscience framework for studying the mechanisms that give rise to cognitive flexibility and support several conclusions about the cognitive and neural architecture of adaptive behavior.

Architecture of cognitive flexibility

We observed a significant effect on cognitive flexibility with lesions in left hemispheric white matter sectors including the superior longitudinal/arcuate fasciculus that connect frontal, temporal, and parietal cortices. Despite its distributed nature, the neural substrates of cognitive flexibility were remarkably circumscribed, concentrated in the core of white matter, and comprising a narrow subset of regions associated with performance on individual WAIS-III subtests. The largest overlap between WAIS-III subtests and cognitive flexibility was found for verbal comprehension, working memory, fluid intelligence, and processing speed. Collectively, these subtests assess verbal knowledge about the world, verbal reasoning, working memory capacity, as well as cognitive flexibility and executive control, and are associated with a distributed fronto-parietal network. This pattern of results suggests that cognitive flexibility draws upon the combination of conceptual knowledge and executive processes, and that the communication between areas associated with these capacities is of critical importance.

The observed findings contribute to a growing body of neuro-psychological patient evidence indicating that damage to a distributed network of frontal and parietal regions is associated with impaired performance on tests of higher cognitive function (Barbey et al., 2012c; Chiang et al., 2009; Colom et al., 2009; Gläscher et al., 2010; Jung and Haier, 2007). The study by Barbey et al. (2012c) applied voxel-based lesion-symptom mapping to elucidate the neural substrates of psychometric g, reporting a left lateralized fronto-parietal network that converges with the observed pattern of findings. Our study contributes to this research program by elucidating the relationship between key competencies of psychometric intelligence and cognitive flexibility — providing evidence that these domains recruit a highly overlapping and broadly distributed network of frontal and parietal regions (see Figs. 2 and 3).

Accumulating evidence indicates that the fronto-parietal network provides an integrated architecture for the coordination and control of cognitive representations (Badre and Wagner, 2006; Barbey et al., 2012c; Gläscher et al., 2010). These mechanisms are critical for the optimal recruitment of internal resources to exhibit goal-directed behavior — supporting conceptual representations and executive processes that provide the basis for cognitive flexibility. We propose that mechanisms for integration and control are carried out by a central system that has extensive access to sensory and motor representations (cf., Miller and Cohen, 2001) and that the fronto-parietal network is at an ideal site in the brain to support these functions. Nodes of this network are thoroughly and reciprocally connected with each other, as well as with other association cortices and subcortical areas, a property that allows widespread access to perceptual and motor representations at multiple levels. With this unique connectivity pattern, and specialization in a wide variety of higher cognitive processes, the fronto-parietal network can function as a source of integration and top-down control in the brain. This framework complements existing neuroscience models by highlighting the importance of the white-matter association tracts (e.g., the arcuate fasciculus) for the integration of cognitive representations in high-level cognition (Jung and Haier, 2007), while also emphasizing the central role of top-down mechanisms within frontal and parietal cortices for the executive control of behavior (Miller and Cohen, 2001). According to this framework, the fronto-parietal network is a core system that supports the integration and control of distributed patterns of neural activity throughout the brain, providing a coordinated architecture for cognitive flexibility.

In addition to investigating cognitive flexibility in relation to a broad spectrum of mental processes (Fig. 1), we examined brain regions that were selectively engaged for cognitive flexibility (while removing the variance associated with its significant predictors). This analysis revealed selective damage to the right anterior superior temporal gyrus (Fig. 4). This brain region is known to support insight and the recognition of novel semantic relations (Jung-Beeman et al., 2004) and suggests that cognitive flexibility embodies mechanisms that support the formation of new semantic relations. This finding indicates that cognitive flexibility centrally depends on neural mechanisms for the integration and synthesis of conceptual knowledge, supporting cognitive insight and enabling people to see connections that previously eluded them.

From a clinical perspective, understanding impairments in cognitive flexibility in patients with brain damage may greatly facilitate the design of appropriate assessment tools and rehabilitation strategies, with potential improvement in patients' cognitive abilities (e.g., problem solving, self-expression, adaptability) and daily living. The reported findings identify markers that may be targeted in clinical investigations to assess the functioning of the fronto-parietal network, particularly, measures of mental flexibility and fluency. The observed findings elucidate brain structures that are engaged by both cognitive flexibility and psychometric intelligence, 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. 1).

It is important to emphasize in closing that the abilities measured by tests of psychometric intelligence, emotional intelligence, and personality do not provide a comprehensive assessment of all human psychological traits. There are other aspects, in addition to those measured here, which contribute to mental life, notably those related to planning and cognitive control (Diamond, 2013). In addition, further research is needed to explore how cognitive flexibility is represented and expressed in different domains (e.g., mathematics, poetry, drama, music, etc.). Understanding the cognitive and neural architecture of mental flexibility will ultimately require a comprehensive assessment that examines a broader scope of issues. The reported findings contribute to this emerging research program by developing a cognitive neuroscience framework for studying adaptive behavior, demonstrating that core elements of cognitive flexibility emerge from a distributed network of brain regions that support specific competencies for human intelligence.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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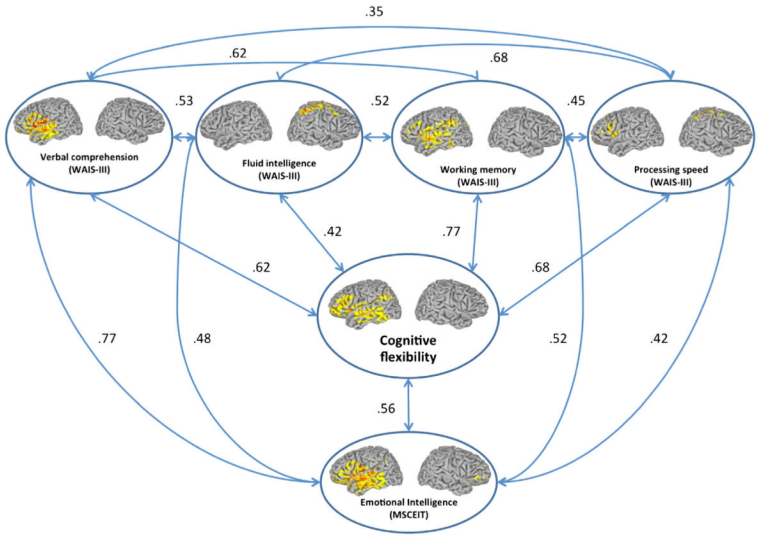

Fig. 1.

Summary of lesion mapping and structural equation modeling results (n = 149). The statistical maps are thresholded at 5% false discovery rate. In each map of the cortical surface, the left hemisphere is on the reader's left. "WAIS-III" stands for Wechsler Adult Intelligence Scale, Third Edition; "MSCEIT" standard for the Mayer, Salovey, Caruso Emotional Intelligence Test.

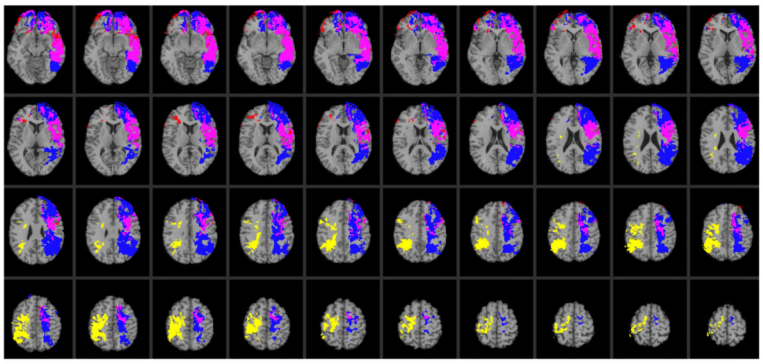

Fig. 2.

Voxel-based lesion-symptom mapping of cognitive flexibility, fluid intelligence, and verbal comprehension. Lesion overlap map illustrating common and distinctive brain regions for cognitive flexibility (blue), fluid intelligence (yellow), and verbal comprehension (red) (n = 149). Overlap between cognitive flexibility and fluid intelligence is illustrated in green. Overlap between cognitive flexibility and verbal comprehension is illustrated in pink. Overlap between fluid intelligence and verbal comprehension 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.

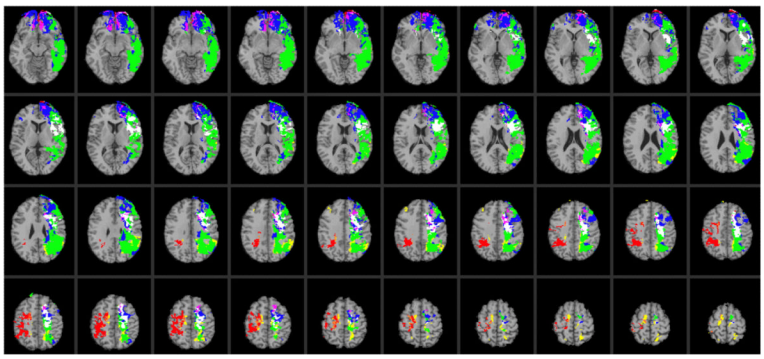

Fig. 3.

Voxel-based lesion-symptom mapping of cognitive flexibility, working memory, and processing speed. Lesion overlap map illustrating common and distinctive brain regions for cognitive flexibility (blue), working memory (yellow) and processing speed (red) (n = 149). Overlap between cognitive flexibility and working memory is illustrated in green. Overlap between cognitive flexibility and processing speed is illustrated in pink. Overlap between working memory and processing speed 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.

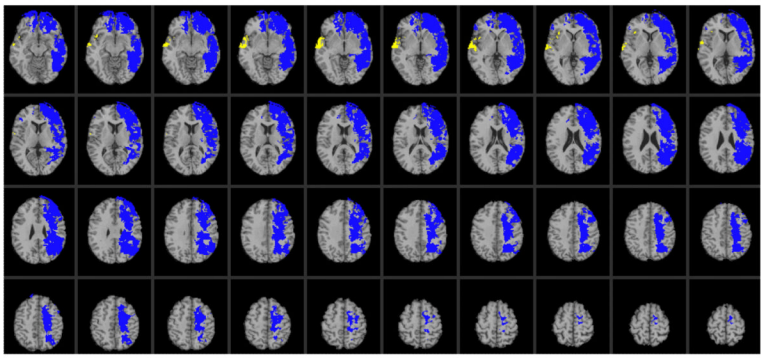

Fig. 4.

Voxel-based lesion-symptom mapping of the unique variance explained by cognitive flexibility. Lesion overlap map illustrating common and distinctive brain regions for cognitive flexibility latent (blue) and cognitive flexibility residual (yellow) ($n = 149$). Overlap between these conditions is illustrated in green. The statistical map is thresholded at 5% false discovery rate. In each axial slice, the right hemisphere is on the reader's left.