

Lesion mapping of social problem solving

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Accumulating neuroscience evidence indicates that human intelligence is supported by a distributed network of frontal and parietal regions that enable complex, goal-directed behaviour. However, the contributions of this network to social aspects of intellectual function remain to be well characterized. Here, we report a human lesion study ($n = 144$) that investigates the neural bases of social problem solving (measured by the Everyday Problem Solving Inventory) and examine the degree to which individual differences in performance are predicted by a broad spectrum of psychological variables, including psychometric intelligence (measured by the Wechsler Adult Intelligence Scale), emotional intelligence (measured by the Mayer, Salovey, Caruso Emotional Intelligence Test), and personality traits (measured by the Neuroticism-Extraversion-Openness Personality Inventory). Scores for each variable were obtained, followed by voxel-based lesion–symptom mapping. Stepwise regression analyses revealed that working memory, processing speed, and emotional intelligence predict individual differences in everyday problem solving. A targeted analysis of specific everyday problem solving domains (involving friends, home management, consumerism, work, information management, and family) revealed psychological variables that selectively contribute to each. Lesion mapping results indicated that social problem solving, psychometric intelligence, and emotional intelligence are supported by a shared network of frontal, temporal, and parietal regions, including white matter association tracts that bind these areas into a coordinated system. The results support an integrative framework for understanding social intelligence and make specific recommendations for the application of the Everyday Problem Solving Inventory to the study of social problem solving in health and disease.

Keywords: social intelligence; latent variable modelling; voxel-based lesion–symptom mapping

Abbreviations: EPSI = Everyday Problem Solving Inventory; MSCEIT = Mayer, Salovey, Caruso Emotional Intelligence Test; NEO-PI = Neuroticism-Extraversion-Openness Personality Inventory; VHIS = Vietnam Head Injury Study; WAIS = Wechsler Adult Intelligence Scale

Introduction

Social problem solving refers to mental processes and strategies for making decisions and solving problems encountered in everyday social life (Cornelius and Caspi, 1987; Dimitrov *et al.*, 1996). This ecological approach to studying problem solving considers the ways in which an individual perceives and structures the problem situation, with a focus on social, emotional, and contextual factors (Diehl *et al.*, 1995; Marsiske and Willis, 1995; Blanchard-Fields *et al.*, 1997; Burton *et al.*, 2006; Thornton *et al.*, 2007; Artistic *et al.*, 2010; Mienaltowski, 2011). According to this approach, the ability to solve a problem is influenced by: (i) whether or not the problem reflects situations encountered in daily life; (ii) the extent to which the problem is personally meaningful or emotionally salient to the individual; (iii) how the individual incorporates social and emotional information to guide thought and drive effective behaviour; and (iv) how adaptive a specific solution is given the individual's goals and context of living.

In recent years neuropsychology has placed increasing importance on broadening the scope of standard cognitive assessments to incorporate social and emotional aspects of intellectual function (Barbey *et al.*, 2009, 2011, 2014a; Kennedy and Adolphs, 2011; Adolphs and Anderson, 2013). In particular, emerging neuroscience evidence indicates that social problem solving may rely upon executive control functions for the regulation and control of behaviour (Miller and Cohen, 2001; Barbey *et al.*, 2012) and recruit brain regions that are specifically oriented toward the resolution of conflict within social and emotional contexts (Sternberg, 2000; Whitfield and Wiggins, 2003; Channon, 2004; Barbey *et al.*, 2014a). Indeed, the ability to interact and communicate effectively in everyday social settings is frequently disrupted by traumatic brain injury and this poses fundamental difficulties for successful rehabilitation (Warschawsky *et al.*, 1997; Janusz *et al.*, 2002; Ganesalingam *et al.*, 2007; Hanten *et al.*, 2008, 2011; Muscara *et al.*, 2008; Robertson and Knight, 2008).

A network of neural correlates has been linked to social and emotional processing using a range of experimental materials, such as interpersonal scenarios, cartoons, jokes, faux pas, and moral and ethical dilemmas (Adolphs, 2003a, b, 2010; Kennedy and Adolphs, 2011). Social cognitive neuroscience research indicates that the medial prefrontal cortex plays a key role in the representation of mental states, both for an individual's own thoughts and beliefs and those of others (Saxe and Kanwisher, 2003); the right posterior superior temporal sulcus mediates the analysis of biological motion or agency, facilitating the interpretation of purposeful movements (Mar *et al.*, 2007); the left temporal pole is involved in storing relevant social knowledge, which contributes to the contextual understanding of others' social interactions (Simmons and Martin, 2009; Simmons *et al.*, 2010); and the orbitofrontal-amygdala regions are involved in emotional aspects of processing (Frith and Frith, 2003; Saxe and Kanwisher, 2003; Sabbagh, 2004; Saxe, 2006).

Neuropsychological patients with focal brain lesions provide a valuable opportunity to study the neural mechanisms of social problem solving, supporting the investigation of lesion-deficit

associations that elucidate the contribution of specific brain structures. Although the neural foundations of social problem solving remain to be directly assessed using lesion methods, the broader neuropsychological patient literature has provided significant insight into the neural bases of social and emotional aspects of intellectual function (Rowe *et al.*, 2001; Stuss *et al.*, 2001; Gregory *et al.*, 2002; Abu-Akel, 2003; Saxe and Kanwisher, 2003; Apperly *et al.*, 2004; Shamay-Tsoory *et al.*, 2003, 2005; Channon *et al.*, 2007). For example, a recent lesion mapping study of emotional intelligence (Barbey *et al.*, 2014a) indicates that the capacity to engage in sophisticated information processing about emotions and to use this information to guide thought and behaviour is supported by a broadly distributed network of frontal, temporal, and parietal regions that have been widely implicated in social cognition (Saxe, 2006). However, the contributions of this network to everyday social problem solving remain to be well characterized. Outstanding questions about the social and emotional nature of everyday problem solving centre on advancing our knowledge of its psychological and neural foundations—investigating how selective damage to specific brain systems impacts performance on everyday problem solving and is related to a host of executive, social, and emotional processes.

Motivated by these considerations, we studied social problem solving by administering the Everyday Problem Solving Inventory (EPSI; Cornelius and Caspi, 1987) to a large sample of patients with focal brain injuries ($n = 144$). We investigated how social problem solving relates to a broad spectrum of psychological variables, including psychometric intelligence [Wechsler Adult Intelligence Scale, WAIS (Wechsler, 1997)]; emotional intelligence [Mayer, Salovey, Caruso Emotional Intelligence Test; MSCEIT (Mayer *et al.*, 2008)], and personality traits [Neuroticism-Extroversion-Openness Personality Inventory, NEO-PI (Costa and McCrae, 2000)]. Our goal was to conduct a comprehensive assessment of social problem solving that examined the contributions of executive, social and emotional information processing abilities, and personality traits. Indeed, the role of personality traits, such as extraversion, agreeableness and conscientiousness, in predicting an individual's ability to manage and resolve conflict in social problem solving contexts remains to be explored.

We applied: (i) confirmatory factor analysis to obtain latent scores of psychometric and emotional intelligence; and (ii) exploratory factor analysis to compute a general everyday problem solving index (EPSI). Standardized scores were considered for the EPSI facets and the personality traits. The scores were submitted to voxel-based lesion-symptom mapping. We investigated: (i) the degree to which individual differences in social problem solving are predicted by general intelligence (measured by the WAIS), emotional intelligence (measured by the MSCEIT), and personality traits (measured by the NEO-PI); and (ii) whether social problem solving engages cortical networks for executive, social, and emotional functions. We hypothesized that social problem solving would recruit neural systems for executive, social, and emotional functions, reflecting a reliance upon mechanisms for the regulation and control of social behaviour.

Materials and methods

Participants

The Vietnam Head Injury Study (VHIS) was set up by William F. Caveness, chief of the Laboratory of Experimental Neurology at the National Institute of Neurological and Communicative Disorders and Stroke from 1965. He designed the VHIS registry, which gathered information on 1221 Vietnam veterans who sustained a traumatic brain injury between 1967 and 1970 (Caveness, 1979). The Vietnam conflict was the first that involved large-scale helicopter evacuations and early treatment by neurosurgical teams close to the battlefield, so that most patients received definitive treatment within hours of their injuries, allowing a much higher rate of survival than in previous conflicts (Rish *et al.*, 1981; Carey *et al.*, 1982). In addition, the low velocity penetrating fragment wounds typically sustained resulted in relatively focal defects, and so these subjects provided a particularly large and informative group for study. Participants were drawn from the Phase 3 VHIS registry, which includes American male veterans who suffered brain damage from penetrating head injuries in the Vietnam War ($n = 144$). This study was approved by the National Institutes of Health Institutional Review Board and, in accordance with stated guidelines, all subjects read and signed informed consent documents. As our participants have had an injury that may have impaired their ability to think clearly and make decisions, we ask that they travel with a primary caregiver and name them as a Durable Power of Attorney for research and medical care at NIH.

Phase 3 testing occurred between April 2003 and November 2006. Demographic and background data for the VHIS are reported in Supplementary Table 1 (Koenigs *et al.*, 2009; Raymond *et al.*, 2010; Barbey *et al.*, 2011, 2012, 2013a, b, 2014b). We observed a significant correlation between years of education and performance on the EPSI (overall), WAIS-III (g), and MSCEIT (overall emotional intelligence score) (ranging from 0.3 to 0.5), consistent with the psychometric literature demonstrating a relationship between education and mental ability (Jensen, 1998). Importantly, however, the pattern of findings obtained from our study remains the same when controlling for years of education, as described below and illustrated in Supplementary Table 5.

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. All non-brain tissue seen in the subject's CT scan was automatically removed (skull-stripped) in order to improve the accuracy of spatial normalization to a CT template brain in MNI space. The spatial normalization was achieved by using the AIR 3.08 algorithm using a 12-parameter affine transformation. Lesion location and volume were determined from CT images using the Analysis of Brain Lesion software (ABLE) (Makale *et al.*, 2002; Solomon *et al.*, 2007) contained in MEDx v3.44 (Medical Numerics) with enhancements to support the Automated Anatomical Labelling atlas (Tzourio-Mazoyer *et al.*, 2002). Within ABLe, the lesions were drawn manually in native space on each 1-mm thick slice by a neuropsychiatrist with clinical experience reading CT scans and reviewed by our team of cognitive neuroscientists, enabling a consensus decision to be reached regarding the limits of

each lesion. For each subject, a lesion mask image in MNI space was saved for voxel-based lesion–symptom mapping (Bates *et al.*, 2003). Although the original scans were acquired with the CT modality, voxel-based lesion symptom mapping results are overlaid on magnetic resonance images in MNI space for better visualization of brain structures. Voxel-based lesion–symptom mapping 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 (FDR) correction of $q < 0.05$. To ensure sufficient statistical power for detecting a lesion-deficit correlation, our analysis only included voxels for which four or more patients had a lesion. The lesion overlap map for the entire VHIS patient sample is illustrated in Supplementary Fig. 1. It is important to emphasize that the conclusions drawn from the VHIS sample are restricted to the voxel space identified in Supplementary Fig. 1, which provides broad coverage of the cerebral hemispheres but does not include subcortical brain structures.

Psychological measures

We administered the EPSI (Cornelius and Caspi, 1987), WAIS-III (Wechsler, 1997) MSCEIT (Mayer, 2004; Mayer *et al.*, 2008), and the NEO-PI (Costa and McCrae, 2000). We applied latent variable modelling (Loehlin, 2004) to derive factor scores for psychometric and emotional intelligence, as reported by Barbey and colleagues (2014a). We also obtained factor scores for the EPSI. Personality traits were measured by the NEO-PI (including extraversion, agreeableness, conscientiousness, neuroticism, and openness to experience), but treated separately from the psychometric intelligence measures. Supplementary Table 2 summarizes the employed measures of psychometric and emotional intelligence (for further detail concerning their standardization, reliability and validity, see Cornelius and Caspi, 1987; Wechsler, 1997; Mayer *et al.*, 2008) along with the measured personality traits.

Barbey *et al.* (2014a) analysed the WAIS-III and the MSCEIT battery at the latent variable level (Loehlin, 2004). The tested measurement model defined emotional intelligence applying the MSCEIT battery, whereas verbal comprehension, perceptual organization/fluid intelligence, working memory, and processing speed defined psychometric intelligence. This model produced appropriate fit indices and all correlations among factors were statistically significant. Barbey *et al.* (2014a) applied the imputation function of the AMOS program (Arbuckle, 2006) to obtain latent scores for these factors.

The EPSI scores for the six facets comprised by this battery were submitted to an exploratory factor analysis to uncover the factor structure underlying everyday problem solving. A principal factor analysis was computed (Fabrigar, 1999). The Kaiser-Meyer-Olkin value was high (0.84) and the Bartlett test produced proper values ($\chi^2 = 318.6$, $df = 15$, $P = 0.000$). One single factor was obtained (eigenvalue = 3.33, % of variance = 55.5) with factor loadings ranging from 0.54 (family conflict resolution) to 0.78 (friend conflict resolution). The factor score for the EPSI battery was obtained using the regression method from the data reduction menu comprised in the SPSS package (SPSS, 2013). These scores were standardized for clarity purposes [mean = 100, standard deviation (SD) = 15]. Finally, the NEO-PI-R scores were also submitted to regression and lesion analyses.

Everyday Problem Solving Inventory

The EPSI is comprised of 48 hypothetical problem situations that represent six content domains (i) friend conflict resolution; (ii) home

management; (iii) consumerism; (iv) work conflict resolution; (v) information management; and (vi) family conflict resolution (Cornelius and Caspi, 1987). For each problem situation, four possible responses were provided to participants. These responses were designed to represent four coping styles: (i) problem focused action; (ii) cognitive problem analysis; (iii) passive-dependent behaviour; and (iv) avoidant thinking and denial. Participants were instructed to imagine that they were in the described situations and were asked to rate the effectiveness of each solution in each of the four response modes provided for each situation. Ratings were made on a 5-point scale (1 = 'extremely ineffective/poor solution' and 5 = 'extremely effective solution'). Participants rated each possible response, producing four ratings for each problem situation. In this study, the EPSI was scored according to the procedure outlined by Cornelius and Caspi (1987): participant responses were correlated with judges' ratings of the effectiveness of each problem solution (Cornelius and Caspi, 1987). Participants' scores represented the degree to which their response patterns approximated optimal response patterns that were identified by judges. Separate scores were obtained for each problem domain as well as for the total measure. The psychometric properties of the EPSI have been well characterized by prior research (Marsiske and Willis, 1995), which supports the validity and reliability of this instrument as a measure of social problem solving (i.e. mental operations for the management and resolution of conflict within each social problem solving domain).

Relationships among scores

Social problem solving was assessed by the EPSI, and verbal comprehension was assessed by the vocabulary, similarities, information and comprehension subtests from the WAIS-III. Perceptual organization/fluid intelligence was measured by block design, matrix reasoning, picture completion, picture arrangement, and object assembly subtests from the WAIS-III. Working memory comprised measures of arithmetic, digit span, and letter-number sequencing from the WAIS-III, and processing speed was assessed by digit symbol coding and symbol search subtests from the WAIS-III. Emotional intelligence was measured by the full MSCEIT battery, including the faces, pictures, sensations, facilitation, blends, changes, emotional, and social subtests. Supplementary Table 3 presents the descriptive statistics for each of the administered tests. Supplementary Table 4 presents the correlation matrix for the scores submitted to lesion analysis. The scores of interest were: EPSI factor score, EPSI facets, WAIS-III factor scores (verbal comprehension, perceptual organization/fluid intelligence, working memory, processing speed), MSCEIT/Emotional Intelligence general factor score, and NEO-PI-R traits (extraversion, agreeableness, conscientiousness, neuroticism, and openness). It is noteworthy that a positive manifold is clear, as evidenced by substantial correlations among scores derived from the cognitive measures (ranging from 0.48 to 0.54). Note also that the observed pattern of correlations were remarkably similar when education was controlled for (Supplementary Table 5).

Voxel-based lesion–symptom mapping

The obtained scores were correlated to regional grey 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 grey 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 (Gläscher *et al.*, 2010; Woolgar *et al.*, 2010; Barbey *et al.*, 2012, 2014a, c).

Results

Stepwise regression analyses

Scores for psychometric intelligence (verbal comprehension, perceptual organization/fluid intelligence, working memory, and processing speed) and emotional intelligence (MSCEIT general factor score) along with the five personality traits were submitted to a forward stepwise regression analysis where EPSI scores were the dependent measures. The SPSS program was used for this latter analysis and it provides the variables predicting the dependent measure once their own correlations are taken into account (SPSS, 2013). The analyses were computed for the total EPSI scores as well as for the six everyday problem solving domains (friend conflict resolution, home management, consumerism, work conflict resolution, information management, and family conflict resolution). Results indicated that the EPSI total score was predicted (adjusted $R^2 = 0.36$, $P < 0.001$) by working memory (Beta = 0.24, $t = 2.47$, $P = 0.015$), processing speed (Beta = 0.21, $t = 2.40$, $P = 0.018$), and emotional intelligence (Beta = 0.27, $t = 3.1$, $P = 0.002$). In addition, each everyday problem solving domain relied upon specific social and intellectual functions. In particular, (i) friend conflict resolution was predicted (adjusted $R^2 = 0.27$, $P < 0.001$) by working memory (Beta = 0.31, $t = 3.3$, $P = 0.001$), processing speed (Beta = 0.21, $t = 2.3$, $P = 0.02$) and openness (Beta = 0.19, $t = 2.6$, $P = 0.01$); (ii) home management was predicted (adjusted $R^2 = 0.17$, $P < 0.001$) by verbal comprehension (Beta = 0.18, $t = 2.1$, $P = 0.04$) and processing speed (Beta = 0.32, $t = 3.7$, $P = 0.00$); (iii) consumerism was predicted (adjusted $R^2 = 0.16$, $P < 0.001$) by perceptual organization/fluid intelligence (Beta = 0.24, $t = 2.6$, $P = 0.01$) and emotional intelligence (Beta = 0.22, $t = 2.4$, $P = 0.02$); (iv) work conflict resolution was predicted (adjusted $R^2 = 0.24$, $P < 0.001$) by verbal comprehension (Beta = 0.27, $t = 2.5$, $P = 0.01$) and working memory (Beta = 0.27, $t = 2.4$, $P = 0.01$); (v) information management was predicted (adjusted $R^2 = 0.23$, $P < 0.001$) by working memory (Beta = 0.20, $t = 1.8$, $P = 0.06$), processing speed (Beta = 0.20, $t = 2.0$, $P = 0.04$), and emotional intelligence (Beta = 0.19, $t = 2.0$, $P = 0.04$); and (vi) family conflict resolution was predicted (adjusted $R^2 = 0.18$, $P < 0.001$) by emotional intelligence (Beta = 0.42, $t = 5.5$, $P = 0.00$) and extraversion (Beta = 0.17, $t = 2.2$, $P = 0.03$). Because, as noted above, education correlated with the EPS scale, the WAIS factors, and the MSCEIT, we ran regression analyses including the education variable as a further predictor. The results revealed that education was never relevant for predicting the EPSI scores. The same predictors were observed for the EPSI factor score, friends, home, consumerism, and family. For work, the predictors were working memory and emotional intelligence (verbal comprehension is no longer a predictor), and for information management the predictors were working memory and processing speed (emotional intelligence was

no longer a predictor). Taken together, these findings indicate that everyday problem solving is associated with key competencies for psychometric intelligence (working memory and processing speed) and emotional intelligence, and suggest that specific everyday problem solving domains rely upon facets of psychometric intelligence (i.e. home management and work conflict resolution), emotional intelligence (i.e. family conflict resolution), or competencies for both (i.e. friend conflict resolution, information management, and consumerism). In addition, the results indicate that personality traits (openness and extraversion) reliably predict friend and family conflict resolution.

Lesion mapping of social problem solving

We applied voxel-based lesion–symptom mapping to elucidate the neural mechanisms of social problem solving, identifying a broadly distributed network of brain regions primarily within the left hemisphere (Fig. 1A and B, Supplementary Table 6). Significant effects encompassed locations for: (i) language processing (e.g. Broca's area and left superior temporal gyrus); (ii) spatial processing (e.g. left inferior and superior parietal cortex); (iii) motor processing (e.g. left somatosensory and primary motor cortex); (iv) working memory (e.g. left dorsolateral prefrontal cortex, left inferior and superior parietal cortex, and left superior temporal gyrus); (v) social and emotional information processing (e.g. orbitofrontal cortex, left temporal pole), in addition to expected locations of major white matter fibre tracts; including (vi) the anterior and dorsal bundle of the superior longitudinal/arcuate fasciculus connecting temporal, parietal, and inferior frontal regions; (vii) the superior fronto-occipital fasciculus connecting dorsolateral prefrontal cortex and the frontal pole with the superior parietal lobule; and (viii) the uncinate fasciculus, which connects anterior temporal cortex and amygdala with orbitofrontal and frontopolar regions. Taken together, these results suggest that social problem solving reflects the ability to effectively integrate executive, social, and emotional processes via a circumscribed set of cortical connections primarily within the left hemisphere.

We further investigated whether the observed neural system shared anatomical substrates with reliable predictors of social problem solving; namely, working memory, processing speed, and emotional intelligence (Fig. 2). A lesion overlap map illustrating the common brain regions identified by each of the voxel-based lesion–symptom analyses of working memory, processing speed, and emotional intelligence indicates that these competencies shared regions primarily within the left insula (Fig. 2; regions highlighted in white). The left insula functions as an integral hub for mediating dynamic interactions between large-scale brain networks involved in externally oriented attention (e.g. executive control) and internally oriented or self-regulated cognition (e.g. social and emotional information processing) (Menon and Uddin, 2010; Jezzini *et al.*, 2012; Simmons *et al.*, 2013). For example, Bushara and colleagues (2001) investigated temporal asynchrony in a ventriloquist task and found insula activation to be important, suggesting that this type of 'social synchrony' arises early in life and is supported by the insula. In summary, the findings provide

additional precision for characterizing the psychological and neural foundations of social problem solving, indicating that the left insula represents a key element of the underlying information processing architecture.

We additionally investigated the neural bases of personality traits that were predictive of social problem solving, including openness to experience and extraversion. However, these personality traits did not reveal reliable patterns of brain damage in our sample.

Lesion mapping of residual social problem solving scores

We analysed the social problem solving residual scores removing variance shared with its significant predictors. Impairment in the social problem solving residual score was associated with selective damage to frontal and parietal brain structures that have been widely implicated in executive (Miller and Cohen, 2001) and social function (Barbey *et al.*, 2014a; Ochsner and Lieberman, 2001; Ochsner, 2004). These regions comprised bilateral orbitofrontal cortex (BA 10), left insula, in addition to major white matter fibre tracts, including the superior longitudinal/arcuate fasciculus and the superior fronto-occipital fasciculus (Fig. 3). The observed findings indicate that everyday social problem solving emerges from the coordination of executive, social, and emotional processes.

Discussion

We investigated the neural bases of social problem solving in a large sample of patients with focal brain injuries ($n = 144$) and systematically examined its relationship with a broad spectrum of psychological variables, including psychometric intelligence (verbal comprehension, perceptual organization/fluid intelligence, working memory, and processing speed), emotional intelligence (MSCEIT general factor score), and personality traits (extraversion, agreeableness, conscientiousness, neuroticism, and openness to experience). The analysis of psychometric, social, and emotional factors was motivated by the hypothesis that social problem solving would engage neural systems for the regulation and control of social and affective behavior. The computed regression analyses revealed that working memory, processing speed, and emotional intelligence reliably predict the general score on the EPSI inventory. This finding indicates that executive and social functions predict individual differences in everyday problem solving. We also analysed the six scales included in the EPSI, namely, friend conflict resolution, home management, consumerism, work conflict resolution, information management, and family conflict resolution, using the same regression approach. The results indicate that specific everyday problem solving domains rely upon facets of psychometric intelligence (i.e. home management and work conflict resolution), emotional intelligence (i.e. family conflict resolution), or competencies for both (i.e. friend conflict resolution, information management, and consumerism). The observed findings indicate that the relationships between these measures, and their neurobiological underpinnings, have complex interdependencies.

In addition, our analysis of personality traits and social problem solving indicates that openness to experience and extraversion

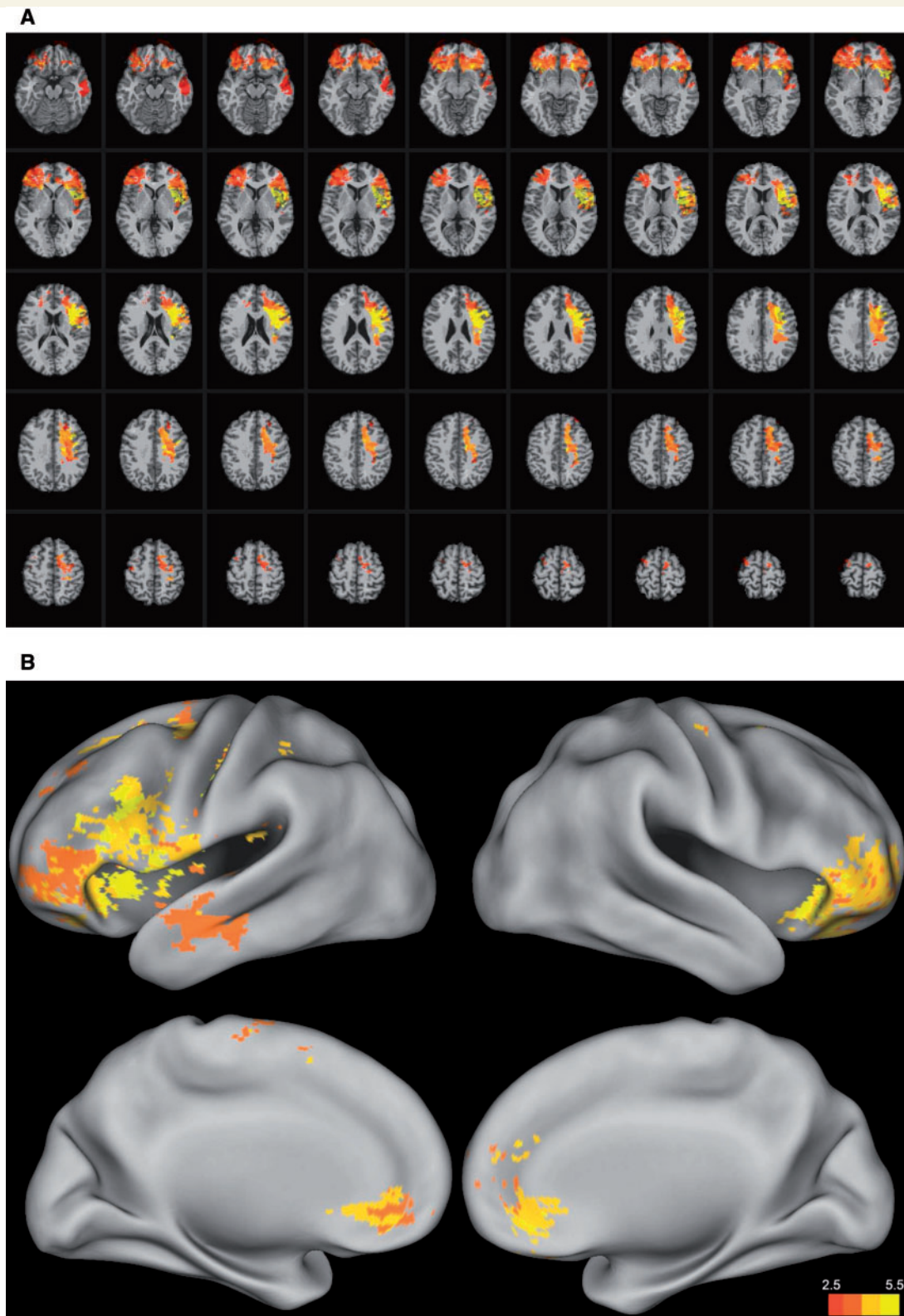


Figure 1 Voxel-based lesion–symptom mapping of everyday problem solving (factor score) ($n = 144$). The statistical map is thresholded at 5% false discovery rate. **(A)** In each axial slice, the right hemisphere is on the reader's left. **(B)** In each inflated map of the cortical surface, the right hemisphere is on the reader's right.

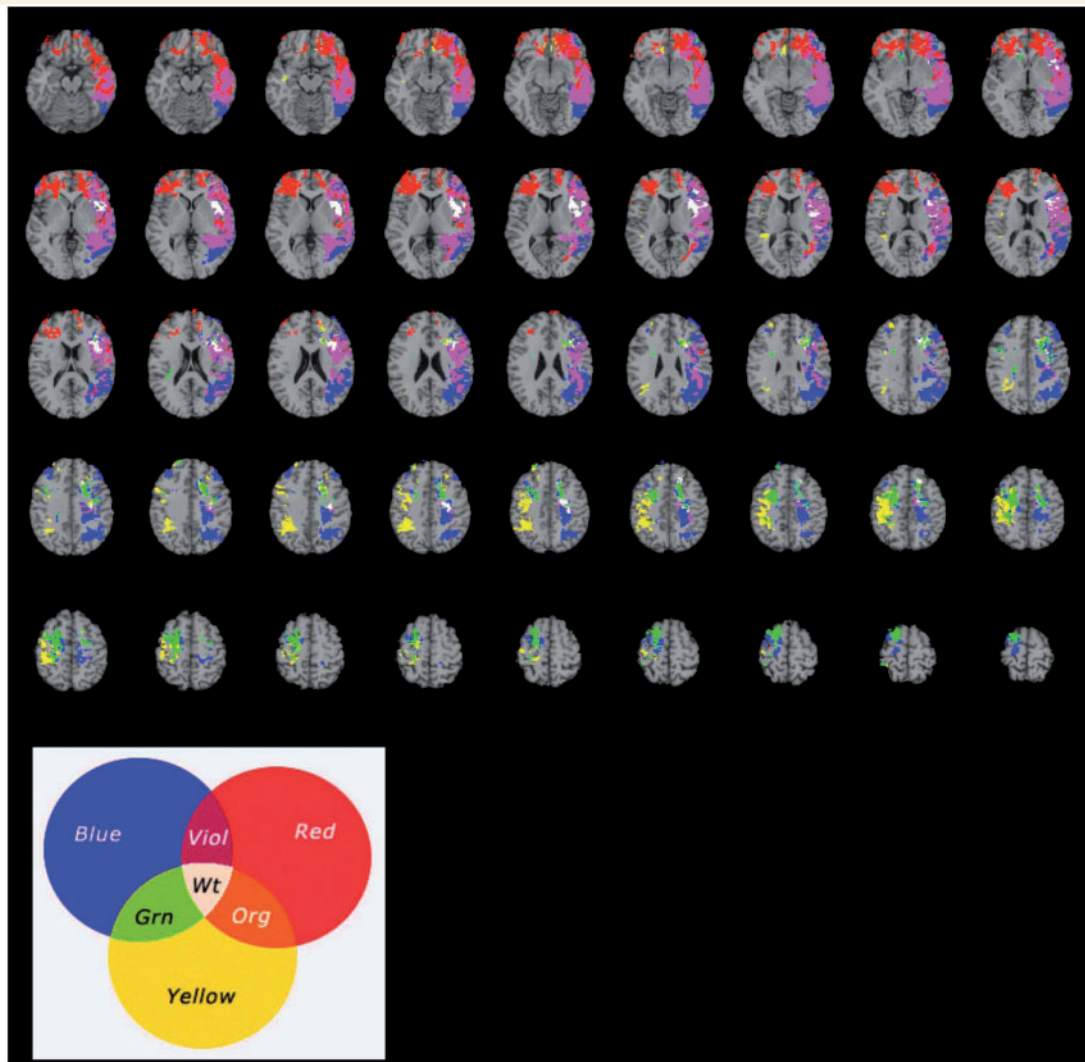


Figure 2 Voxel-based lesion–symptom mapping of the reliable predictors of everyday problem solving (factor score): working memory (blue); processing speed (yellow); and emotional intelligence (red) ($n = 144$). Each statistical map is thresholded at 5% false discovery rate. In each axial slice, the right hemisphere is on the reader's left. Viol = violet; Org = orange; Grn = green; Wt = white.

reliably predict conflict resolution involving friends and family. Individuals high in openness to experience are motivated to seek new social experiences and to engage in self-examination (DeYoung *et al.*, 2014), which together may serve to promote effective problem solving with friends and family. Furthermore, extraversion is a personality trait that is characterized by high energy, enthusiasm, and assertiveness (Quilty *et al.*, 2014), and is known to promote social engagement, which may facilitate social problem solving among friends and family.

Lesion mapping of social problem solving

Voxel-based lesion–symptom mapping for social problem solving and its reliable predictors revealed that both engage a shared network of frontal, temporal, and parietal regions. To develop a rigorous and quantitative approach for studying social problem solving, we related scores derived from the EPSI inventory with several

psychometric and socio-emotional measures. We observed a significant effect on social problem solving with lesions in a distributed network of frontal, temporal, and parietal regions, including white matter association tracts, binding these areas into a coordinated system (Fig. 1A and B, Supplementary Table 6).

The neural substrates of social problem solving were relatively circumscribed, concentrated in the core of white matter, and comprising a narrow subset of regions associated with performance on WAIS-III factors (Fig. 1A and B). The largest overlap between the WAIS-III and social problem solving was found for working memory and emotional intelligence (Table 1). These factors assess operations for adaptive behaviour and social problem solving, and are associated with a distributed fronto-parietal network (Barbey *et al.*, 2012, 2014a). This pattern of findings suggests that social problem solving engages key competencies for psychometric intelligence (e.g., working memory and processing speed) and that the communication between areas associated with these competencies is of critical importance.

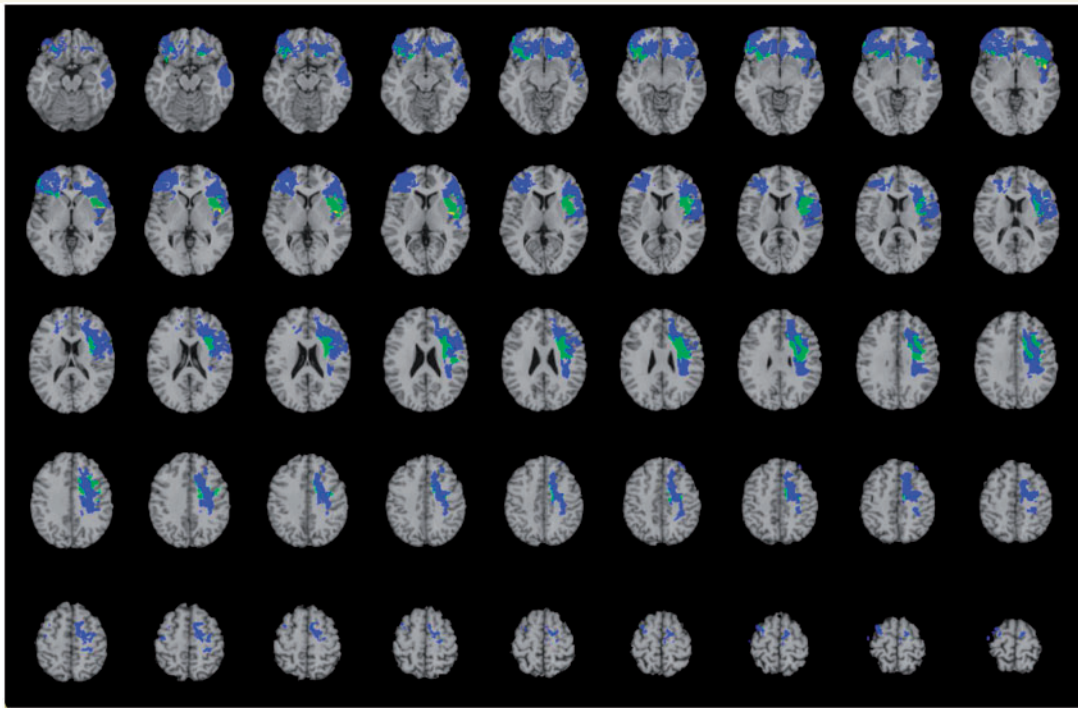


Figure 3 Voxel-based lesion–symptom mapping of the reliable predictors of everyday problem solving for the original and residual factors ($n = 144$). Lesion overlap map illustrating common and distinctive brain regions for everyday problem solving (blue) and everyday problem solving residual (yellow). 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.

Table 1 Spatial overlap between lesion mapping results for EPSI and Working Memory, Processing Speed, and Emotional Intelligence (IQ)

		Thresholded (Dice coefficient)
EPSI with	Emotional IQ	0.49
	Working memory	0.48
	Processing speed	0.22

Overlap statistics were computed using the Dice coefficient (FDR $q = 0.05$). The Dice coefficient has been used in functional MRI analyses to measure the degree of similarity between superthreshold 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) superthreshold voxels, divided by the average total superthreshold voxels of the images. The Dice coefficient is easy to interpret because the maximum value of 1 indicates perfect similarity whereas the minimum value of 0 indicates no similarity.

Lesion mapping of social problem solving residual scores

We further investigated the neural basis of social problem solving while removing the variance shared with its significant predictors. This analysis revealed selective damage to frontal and parietal brain structures that have been widely implicated in executive (Barbey *et al.*, 2014c) and social function (Ochsner and

Lieberman, 2001; Ochsner, 2004). These regions comprised bilateral orbitofrontal cortex (Brodmann area 10), left insula, in addition to major white matter fiber tracts, including the superior longitudinal/arcuate fasciculus and the superior fronto-occipital fasciculus (Fig. 3).

A distributed neural system for social intelligence

The observed findings contribute to neuropsychological 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 (Jung and Haier, 2007; Chiang *et al.*, 2009; Colom *et al.*, 2009; Gläscher *et al.*, 2010). Gläscher *et al.* (2010) 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 pattern of findings observed here. The present study contributes to this research program by elucidating the relationship between key competencies of psychometric intelligence and everyday social problem solving—providing evidence that these domains recruit a highly overlapping and broadly distributed network of frontal and parietal regions (Fig. 1A and B, and Fig. 3).

The available evidence indicates that the fronto-parietal network supports the integration and control of cognitive, social, and emotional representations (Gläscher *et al.*, 2010; Barbey *et al.*, 2012). Mechanisms for integration and control are critical for the optimal

recruitment of internal resources to exhibit goal-directed behaviour—supporting executive functions that provide the basis for everyday social problem solving. 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 supports these functions. Elements of this network are 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 connectivity pattern and specialization in a wide variety of higher cognitive processes—including general intelligence (Barbey *et al.*, 2012), fluid intelligence (Barbey *et al.*, 2014c), cognitive flexibility (Barbey *et al.*, 2013a), working memory (Barbey *et al.*, 2011, 2013b), and emotional intelligence (Barbey *et al.*, 2014a)—the fronto-parietal network can function as a source of integration and top-down control in the brain. This framework therefore complements existing neuroscience models by highlighting the importance of white-matter association tracts (e.g. the arcuate fasciculus) for the integration of cognitive, social, and emotional representations (Barbey *et al.*, 2014a), while also emphasizing the central role of top-down mechanisms within frontal and parietal cortices for the executive control of behaviour (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 an integrative architecture for key competencies of psychometric, social, and emotional intelligence. Although we have observed preferential recruitment of this system in the left hemisphere, evidence also exists for the engagement of this network in the right hemisphere (Barbey *et al.*, 2014c), motivating further research on the principles that guide left versus right hemisphere systems for everyday problem solving.

Clinical implications

From a clinical perspective, understanding impairments in everyday social problem solving may facilitate the design of appropriate assessment tools and rehabilitation strategies for patients with brain injuries, with potential improvement in patients' social abilities and daily living (Warschawsky *et al.*, 1997; Janusz *et al.*, 2002; Ganesalingam *et al.*, 2007; Hanten *et al.*, 2008, 2011; Muscara *et al.*, 2008; Robertson and Knight, 2008). The reported findings provide neuropsychological patient evidence linking impairments in everyday problem solving to particular profiles of brain damage. Indeed, the reported results support inferences about executive and social impairments that accompany damage to specific cortical networks and can be productively applied in a clinical setting: (i) to help explain why an individual is experiencing difficulties in these areas (i.e. due to damage to the underlying neural mechanisms); and (ii) to help predict the executive, social, and emotional processes that are likely to be impaired in the patient and to apply this knowledge to guide the selection of targeted clinical therapies.

The reported findings contribute to classic neuropsychological patient evidence on the consequences of prefrontal cortex damage for human problem solving. It has long been argued that patients with prefrontal cortex lesions have impairments in decision making and problem solving in real-world contexts, particularly problems

involving planning and prediction (Penfield, 1935; Rylander and Frey, 1939; Harlow, 1999). However, a growing number of investigators have questioned the ability to capture and characterize these deficits adequately using standard neuropsychological measures and have called for tests that reflect real-world task requirements more accurately (Shallice and Burgess, 1991; Bechara *et al.*, 1994). Indeed, the present study contributes to this effort, providing neuropsychological evidence from a large sample of patients with focal brain lesions to help characterize the neural architecture of social problem solving in everyday, ecologically valid decision contexts.

Conclusion

It is important to emphasize in closing that although the reported findings are obtained from a remarkable sample of well-characterized human lesion patients, conclusions drawn from this population are restricted to adult males and assess brain-behaviour relationships only within the cerebral cortex (and not involving subcortical brain structures) (Burgaleta *et al.*, 2014). We note that the neuroscience literature on human intelligence includes indications that the neural substrates of *g* may vary by gender (Haier *et al.*, 2005), an issue that we are unable to address in the current study. In addition, although we have made an effort to incorporate as many potentially relevant factors as possible in our analyses, the abilities measured by tests of everyday problem solving, 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 may contribute to social problem solving, notably those related to understanding the complex interplay between executive, social, and emotional processes in dynamic social settings. Indeed, the EPSI is a verbal laboratory-based problem solving task that requires more of the left hemisphere's representations and processes particularly given that it is a forced-choice recognition task. Although task performance may represent the kind of deliberative processes that are required in real-life and in real-time, real-life interactions have many more cues and varying contextual circumstances making a one-to-one correspondence unlikely. Finally, additional research is needed to explore how mechanisms for social problem solving are related to a broader range of ecological contexts for social and emotional processing. Understanding the psychological and neural architecture of social problem solving 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 everyday problem solving, demonstrating that social and emotional aspects of intellectual function emerge from an integrated network of brain regions that enable adaptive reasoning and problem solving in everyday social life.

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Supplementary material

Supplementary material is available at *Brain* online.

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