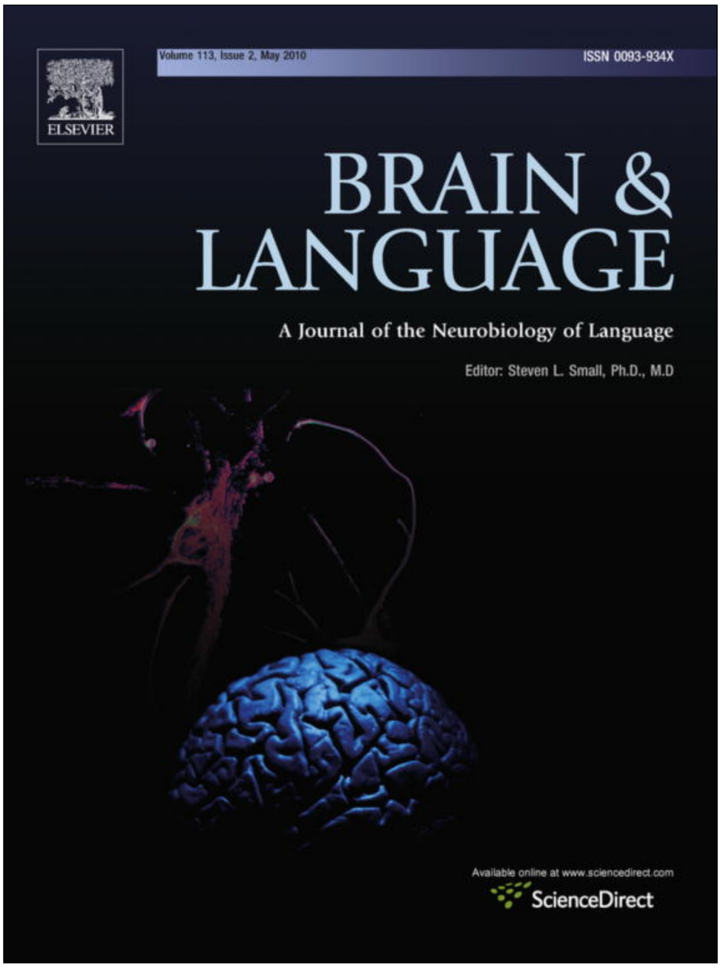
Volume 113, Issue 2, May 2010
ISSN 0093-934X
ELSEVIER
BRAIN & LANGUAGE
A Journal of the Neurobiology of Language
Editor: Steven L. Small, Ph.D., M.D
Available online at www.sciencedirect.com
ScienceDirect

Brain & Language 113 (2010) 59–64

Contents lists available at ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l

Is relational reasoning dependent on language? A voxel-based lesion symptom mapping study

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ARTICLE INFO

Article history:
Accepted 20 January 2010
Available online 5 March 2010

Keywords:
Aphasia
Language
Reasoning
Temporal lobe
Lesion mapping
Problem-solving
Executive functioning

ABSTRACT

Previous studies with brain-injured patients have suggested that language abilities are necessary for complex problem-solving, even when tasks are non-verbal. In the current study, we tested this notion by analyzing behavioral and neuroimaging data from a large group of left-hemisphere stroke patients ($n = 107$) suffering from a range of language impairment from none to severe. Patients were tested on the Raven's Colored Progressive Matrices (RCPM), a non-verbal test of reasoning that requires participants to complete a visual pattern or sequence with one of six possible choices. For some items, the solution could be determined by visual pattern-matching, but other items required more complex, relational reasoning. As predicted, performance on the relational-reasoning items was disproportionately affected in language-impaired patients with aphasia, relative to non-aphasic, left-hemisphere patients. A voxel-based lesion symptom mapping (VLSM) procedure was used to relate patients' RCPM performance with areas of damage in the brain. Results showed that deficits on the relational reasoning problems were associated with lesions in the left middle and superior temporal gyri, regions essential for language processing, as well as in the left inferior parietal lobule. In contrast, the visual pattern-matching condition was associated with lesions in posterior portions of the left hemisphere that subserve visual processing, namely, occipital and inferotemporal cortex. These findings provide compelling support for the idea that language is critical for higher-level reasoning and problem-solving.

1. Introduction

The ability to reason and problem-solve is a critical component of human behavior. Although non-human primates and other animals also possess this capability, reasoning abilities appear to be most advanced in humans (Halford, Wilson, & Phillips, 1998; Kuczaj & Hendry, 2003; Penn, Holyoak, & Povinelli, 2008). One possible explanation for this enhanced ability is that human language serves to bolster our capacity for reasoning and problem-solving (Baldo et al., 2005; Carruthers, 2002; Gentner, 2003; Goel & Dolan, 2004; Sokolov, 1972). Evidence for this notion comes from a variety of studies involving young children as well as language-impaired patients (Hermer-Vazquez, Spelke, & Katsnelson, 1999; Hjelmquist, 1989; Hurlburt, 1990; Kertesz & McCabe, 1975; Sokolov, 1972). For example, Baldo et al. (2005) found that patients with aphasia were impaired on the Wisconsin Card Sorting Test (WCST), which requires examinees to sort cards on the basis of color, shape, and number, while the sorting rule repeatedly changes. The more severe the language impairment, the greater difficulty patients had switching from one sorting criterion to another. In a second experiment, normal individuals were also impaired on the WCST when they had to perform the task under conditions of concurrent articulation (saying "na na na..."). Taken together, these results suggested that executing higher-level problem-solving tasks depends in part on the language system. The current study sought to extend these findings by testing whether non-verbal reasoning, as measured by performance on a standard matrix reasoning task, was also impaired in patients with aphasia.

One of the most commonly used measures of non-verbal reasoning is the Raven's Matrices tests, which include the Raven's Coloured Progressive Matrices (RCPM; Raven, 1962). These tests, variants of which are commonly used in measures of IQ, require individuals to decide which of several stimuli best completes a visual pattern or sequence (see Fig. 1). Some of these problems require relational reasoning, which involves the ability to identify and integrate two or more dimensions of relational change (Christoff et al., 2001). Early studies using the Raven's Matrices tests with language-impaired patients produced mixed results. Some studies

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0093-934X/$ - see front matter Published by Elsevier Inc.
doi:10.1016/j.bandl.2010.01.004

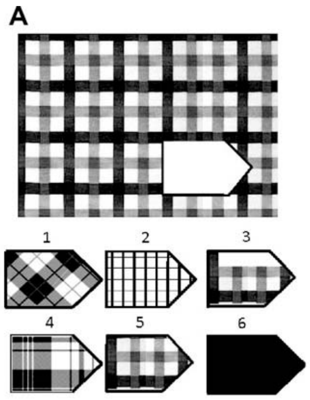

Fig. 1. Examples of the types of problems tested in the RCPM: (A) visual-match and (B) relational reasoning. Note that due to copyright issues, these examples only portray the types of problems on the RCPM, not actual items from the test.

reported disproportionate impairment in aphasic individuals (e.g., Basso, Capitani, Luzzatti, & Spinnler, 1981; Basso, De Renzi, Faglioni, Scotti, & Spinnler, 1973), as one would predict if language plays a crucial role in reasoning. However, other studies failed to find such a difference (e.g., De Renzi & Faglioni, 1965). These early studies were limited by a number of factors, including heterogeneous patient groups and small sample sizes. In addition, such studies did not tease apart the types of items that aphasic patients failed on, but rather analyzed the Raven's Matrices scores as a whole. In fact, only a subset of the Raven's items require relational reasoning, while other items can be successfully completed with visual pattern-matching (DeShon, Chan, & Weissbein, 1995; Villardita, 1985; see Fig. 1 for examples).

In the current study, we tested aphasic patients' performance on the RCPM test, examining separately their performance on problems that require visual pattern-matching and those that require relational reasoning. We tested the prediction that relational reasoning, in particular, would be sensitive to a disruption of language. Further, we sought to identify brain regions that are critical for performance on these two types of problems. The current study used voxel-based lesion symptom mapping (VLSM; Bates et al., 2003), which allows for a voxel by voxel analysis of the relationship between lesion site and performance on a given behavioral measure. VLSM allows for the analysis of patients with a broad range of lesion sites and sizes, thus offering the ability to test brain-behavior relationships independent of pre-specified brain regions or patient groups. Voxels are tested for their relationship to the behavioral measure, in a manner similar to functional neuroimaging methods. Given our hypothesis concerning the relationship between reasoning and language, we predicted that relational reasoning would be associated with lesions in core language areas in the left middle temporal gyrus (Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004; Dronkers & Baldo, 2009), while visual pattern-matching would be most affected by lesions in posterior, visual-processing regions.

2. Methods

2.1. Participants

The study was based on data from 107 left-hemisphere stroke patients (81 male) who were tested as part of a larger neuropsychological study. Inclusion criteria for the study were the following: a single, left-hemisphere stroke; right-handed; normal or corrected-to-normal vision (with no evidence of neglect); native English-speaking; and no pre-morbid history of psychiatric or neurologic diagnoses. Patients' mean age was 60.2 (SD = 10.8), mean education was 14.4 years (SD = 3.0), and mean months post-onset was 50.1 (SD = 50.8). All study participants signed consent forms, and the study was approved by the local Institutional Review Board and was in compliance with the Helsinki Declaration for protection of human subjects.

2.2. Materials and procedures

2.2.1. Behavioral testing

Participants were administered a series of behavioral tests as part of a large neuropsychological battery that took 2–4 sessions to complete. Patients were tested in the chronic phase of their illness (at least 12 months post-onset), so that behaviors were stable. As a measure of speech and language ability, participants were administered the Western Aphasia Battery (WAB; Kertesz, 1982), which tests different aspects of language, including fluency, comprehension, repetition, and naming. An overall aphasia quotient (AQ) is a summary score that is derived from these subtests and provides an indication of aphasia severity. An AQ score of 93.7 or above (out of 100) is considered within normal limits (WNL). The WAB also categorizes patients in terms of aphasia type. The current sample included patients with Broca's aphasia ($n = 23$), Wernicke's aphasia ($n = 10$), conduction aphasia ($n = 4$), global aphasia ($n = 3$), transcortical sensory aphasia ($n = 1$), and anomic aphasia ($n = 29$). Additionally, the sample included patients who were unclassifiable on the WAB ($n = 8$), but who nonetheless scored in the aphasic range (i.e., below 93.7). Last, 29 patients tested within normal limits on the WAB (i.e., AQ $\geqslant$ 93.7); these patients served as a non-aphasic control group for the behavioral analyses presented below.

Participants were also administered the RCPM, a test originally designed to be used as a measure of non-verbal reasoning and intelligence. The RCPM is part of the standard administration of the WAB and thus is routinely administered to our research patients. The RCPM requires only a pointing response, and instructions for the task can be given completely non-verbally so that even severe aphasic patients can complete the task. All patients in the current study were able to comply with test instructions. Examinees were instructed to point to one of six choices that they thought best completed the design or sequence, and they were given as much time as needed to respond. The RCPM includes 36 problems, divided across three sets. Of these problems, we identified *a priori* 17 that could be solved by visual pattern-matching (see left side of Fig. 1), and 10 that required relational reasoning (see right side of Fig. 1). Percentage correct on these two conditions was calculated for each patient.

2.2.2. Lesion analysis

Lesions were either traced directly on the brain images using MRIcro (Rorden & Brett, 2000) or were reconstructed onto standardized brain templates by a board-certified neurologist who was blind to the patients' behavioral presentation. In the former case, lesions were drawn on the patient's T1 image in native space. The patient's brain image was then registered with the MNI template using the standard nonlinear spatial normalization procedure from SPM2 (Statistical Parametric Mapping, Wellcome Trust Centre for Neuroimaging), with cost function masking to avoid distortions due to the lesion itself (Brett, Leff, Rorden, & Ashburner, 2001). In the latter case, the template brain was manually transformed to a commonly used single subject's brain in MNI space. This transformation was nonlinear and was determined slice by slice by matching manually selected control points in the two brains using a local weighted mean transformation implemented by the *cpselect*, *cp2tform* and *imtransform* functions in MATLAB 6.5 (Mathworks, Natick, MA). An overlay of all 107 patients' lesions is shown in Fig. 2. Mean lesion volume was 111.0 cc (SD = 90.6).

Next, we used voxel-based lesion symptom mapping (VLSM; see Bates et al., 2003) to determine the neural correlates of performance on the RCPM. A general linear model (GLM) was fit at each voxel, relating behavioral performance on the RCPM to lesion intensity (0 or 1). Tests were confined to those voxels for which there were at least ten patients with and ten patients without a lesion. A statistical threshold cut-off (t-value) was determined based on permutation testing ($n = 1000$) with *alpha* set at .05 (see Kimberg, Coslett, & Schwartz, 2007). Specifically, we randomly reassigned the patients' behavioral scores 1000 times, and for each permutated dataset, we refit the GLM and recorded the size of the largest t-values. The critical cut-off value in the visual-match condition was $t = 5.14$ and for the relational-reasoning condition, $t = 4.11$.

In order to aid interpretation of the VLSM maps, we also generated a map showing the distribution of power, based on a large effect size (0.8) and an alpha of .05 (see Fig. 3; Cohen, 1988; Cohen, 1992; Kimberg et al., 2007). As can be seen, there was adequate power in a large portion of the left hemisphere, excepting the most anterior, inferior, and posterior regions, since patients suffered from predominantly middle cerebral artery strokes. Our predictions were confined to those regions with sufficient power (i.e., at least 0.8).

3. Results

3.1. Behavioral findings

To determine the role of language in RCPM performance, we compared performance in two groups of patients: those diagnosed with aphasia and those who performed within normal limits (WNL) on the Western Aphasia Battery. Data from the RCPM were analyzed using a repeated measures analysis of covariance with Patient Type as the between-subjects factor (aphasic vs. WNL), Condition as the within-subjects factor (visual-match vs. relational-reasoning), and Percent Correct as the dependent variable. There was a main effect of Patient Type, $F(1, 105) = 21.82$, $p < .001$, with aphasic patients performing worse overall, and a main effect of Condition, $F(1, 105) = 195.91$, $p < .001$, as performance was worse overall in the relational-reasoning condition. As predicted, there was a significant interaction between Patient Type and Condition, $F(1, 105) = 19.41$, $p < .001$, such that the aphasic patients were disproportionately impaired on the relational-reasoning condition. As can be seen in Fig. 4, both aphasic and WNL patients performed well on the visual-match condition (90.6 vs. 97.4% correct, respectively, where chance is 16.7%). However, the aphasic patients' performance was significantly reduced on the reasoning condition relative to WNL patients (44.1 vs. 73.1% correct).

Due to concern about potential ceiling effects on the visual-match condition, we also ran a separate ANOVA, using data from only the bottom half of performers on the visual-match condition. The interaction was still significant, $F(1, 51) = 5.44$, $p < .05$, as were the main effects of Patient Type, $F(1, 51) = 12.10$, $p = .001$, and Condition, $F(1, 51) = 131.73$, $p < .001$. Last, due to concerns about potentially confounding variables, we re-ran the analysis using age, education, months post-onset, and lesion volume as covariates and found that the interaction of Patient Type and Condition remained significant, $F(1, 95) = 5.17$, $p < .05$. However, the main effect of Condition did not reach significance, $F(1, 95) = 3.56$, *ns*, and neither did the main effect of Patient Type, $F(1, 95) = 3.12$, *ns*.

We also ran correlational analyses to measure the relationship between language and reasoning performance. As predicted, and in keeping with the ANOVA results above, the relationship between overall language severity (WAB AQ) was more highly correlated with performance on the relational-reasoning condition, $r = .54$, than the visual-match condition, $r = .41$, both $ps < .01$. The difference between these two correlations was tested using Hotelling's t-test for bivariate correlation comparisons, and the difference approached significance, $Z = 1.58$, where Z-critical for $p < .05 = 1.65$.

Because the sample sizes of the aphasia subtypes were varied and some samples quite small, we did not statistically analyze RCPM performance based on aphasia type. However, behavioral results are shown separately for each group in Fig. 5. Mirroring the above findings, patients with the more severe forms of aphasia

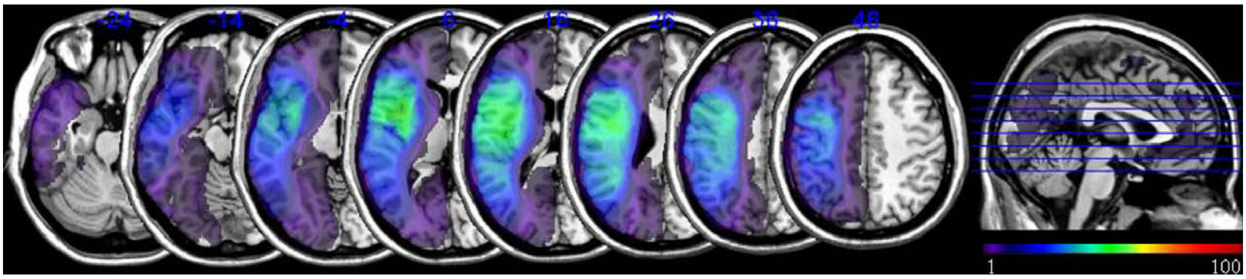

Fig. 2. Overlay of all 107 patients' lesions. Brighter areas represent areas of greater lesion overlap, with green representing approximately half of the sample (see color bar).

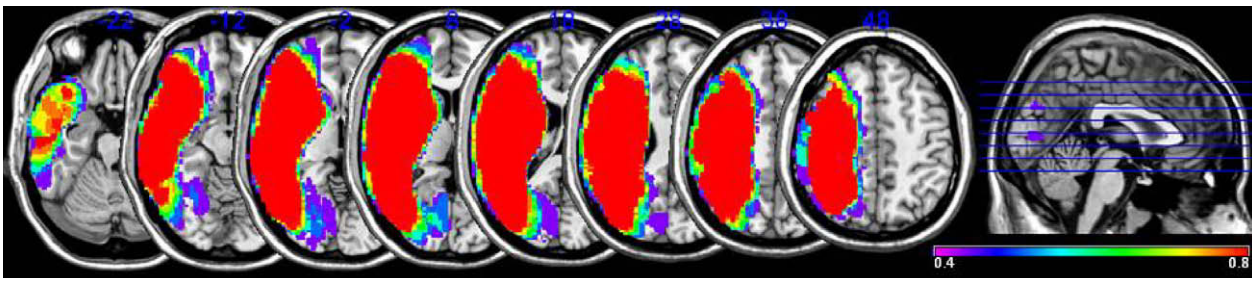

Fig. 3. Map showing distribution of power, ranging from 0.4 (in magenta) to 0.8 (in red), with alpha set to $p < .05$.

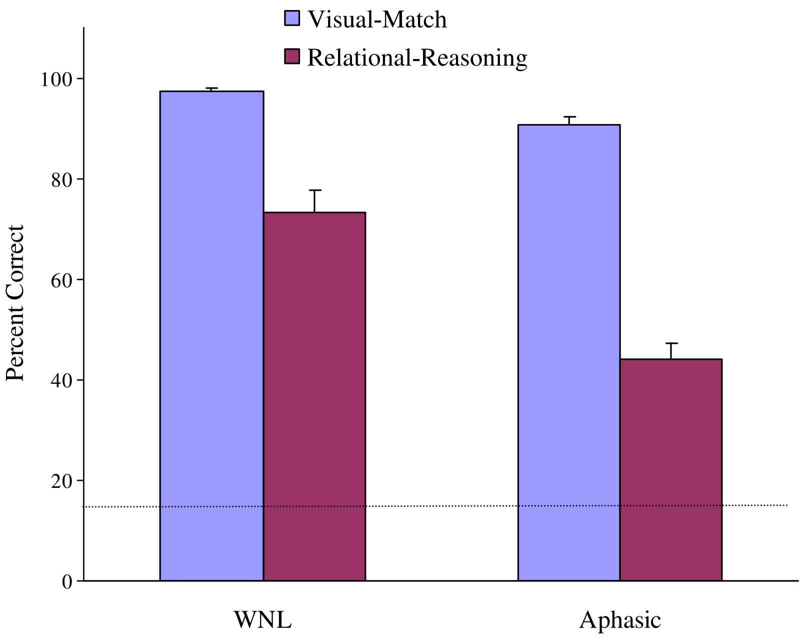

Fig. 4. Performance on the visual-match vs. relational-reasoning condition on the RCPM in patients diagnosed as aphasic vs. within normal limits (WNL) on the language battery. The reference line shows chance performance of 16.7%.

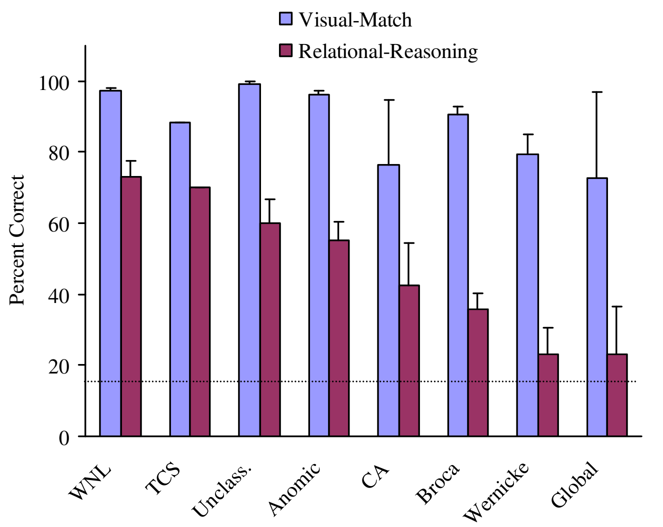

Fig. 5. Performance on the visual-match vs. relational-reasoning condition on the RCPM as a factor of aphasia subtype. The reference line shows chance performance of 16.7%. WNL = within normal limits; TCS = transcortical sensory aphasia; Unclass. = unclassifiable; CA = conduction aphasia.

(i.e., Broca's, global, and Wernicke's) showed the greatest numerical discrepancy in performance between the visual-match and relational-reasoning conditions. Importantly, it was not simply the case that the more severely affected aphasia patients performed worse overall. For example, as can be seen in Fig. 5, patients with Broca's aphasia scored quite well on the visual-match condition, but their performance dropped off precipitously in the relational-reasoning condition.

3.2. Lesion findings

To determine the neural correlates of RCPM performance, VLSM maps were generated from patients' performance on the visual-match and relational-reasoning conditions (see Fig. 6). As predicted, performance on the relational-reasoning condition was associated primarily with lesions in core language areas, specifically, the left middle and superior temporal gyri (Brodmann's area (BA) 21/22; centered at MNI coordinates −60, −20, 0). There was also a smaller region of significance in inferior parietal cortex (BA39/40; centered at −54, −54, 36). In contrast, performance on the visual-match condition was found to be most dependent on posterior areas, including the left posterior inferior temporal gyrus (BA20; centered at −54, −50, −12), visual association cortex (BA 19; −46, −73, −7), and a portion of the optic radiations.

To insure that the findings were robust, we re-ran the VLSM analyses using the visual-match condition as a covariate for the relational-reasoning condition and vice versa. The same set of regions described above remained statistically significant, albeit with smaller cluster sizes.

4. Discussion

In the current study, we tested a large group of left hemisphere patients with a range of language impairment on the RCPM, a nonverbal reasoning task. As predicted, aphasic patients were disproportionately impaired on items requiring relational reasoning, relative to items requiring visual pattern-matching. Moreover, the most severely aphasic patients (i.e., Broca's, global, and Wernicke's aphasics) had the lowest scores, approaching chance performance on the relational-reasoning items. These data provide further support for the notion that language plays an important role in higher-level reasoning. In parallel with these behavioral findings, VLSM maps revealed that relational-reasoning was most dependent on regions in the left middle and superior temporal gyri (regions typically associated with core language processes), while the visual-match items were associated uniquely with left inferior temporal cortex and visual association areas in the left occipital lobe, areas critical for visual processing.

The current findings shed light on prior findings relating to performance on the Raven's matrices by patients with aphasia. Like this study, some earlier studies had found that aphasia was associated with reduced performance on the task (Basso et al., 1973; Bas-

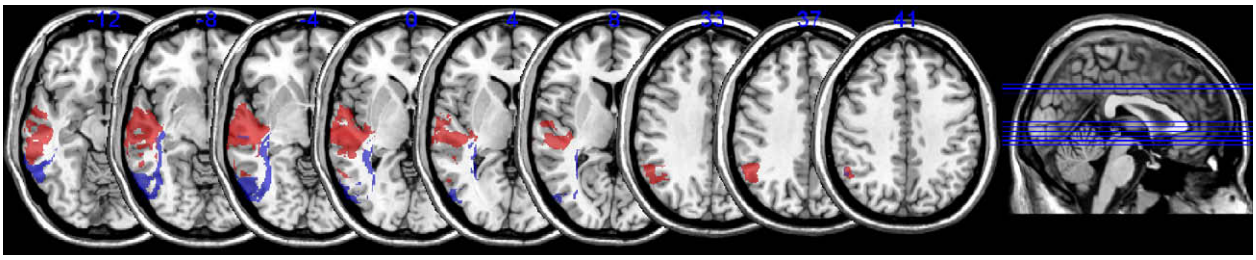

Fig. 6. VLSM map showing lesion correlates of poor performance on the relational-reasoning condition (red) and visual-match condition (blue) of the RCPM. Relational reasoning was most affected by lesions in the left middle and superior temporal gyri, as well as inferior parietal cortex. Performance on the visual-match condition was uniquely affected by lesions in left inferior temporal cortex, the optic radiations, and visual association cortex in the occipital lobe. Only significant voxels are shown based on a critical threshold determined by permutation testing ($p < .05$).

so et al., 1981), although other studies did not (De Renzi & Faglioni, 1965). However, when patients were separated into subgroups, it was found that patients with greater core language impairment (e.g., Wernicke's, global) were most impaired (e.g., Archibald, Wepman, & Jones, 1967; Kertesz & McCabe, 1975). This finding is consistent with the current results in terms of the behavioral findings, in that Wernicke's and global aphasics were most impaired. These earlier studies did not compare performance on different types of Raven's items, however, nor did they have access to detailed imaging data as in the current study.

The present study also extends the conclusions in our previous report of aphasic patients' performance on the Wisconsin Card Sorting Test (WCST; Baldo et al., 2005). Like the RCPM, the WCST is also a non-verbal measure of problem-solving; it requires participants to sort cards based on a series of changing rules (i.e., sort by color, shape, and then number). Similar to the current findings, there was a significant relationship between aphasia severity and performance deficits on the problem-solving task. In addition, like the current findings, the left middle and superior temporal gyri were critical for performance on the WCST.

The current data are also consistent with a case reported by Dronkers, Ludy, and Redfern (1998) of impaired RCPM performance in a neurologically intact woman with reduced language capacity. She was congenitally deaf and did not receive any language instruction until the age of 32. Her language was impoverished with almost non-existent syntax and morphology, though she was able to communicate by stringing together vocabulary words. Like the aphasic patients in the current study, she did not have difficulty identifying the correct response for the visual-match items on the RCPM (100% correct), but was severely impaired on the relational-reasoning items (20% correct). Again, this finding speaks to the critical role that language plays in non-verbal reasoning.

The current study included a large number of aphasic patients and provides several lines of evidence for the role of language in reasoning. Further, this study features a double dissociation between brain regions critical for RCPM problems that require relational-reasoning and those that require visual-matching. However, several limitations of this study should be noted. These data were analyzed retrospectively using a standardized task with a limited number of stimuli, and therefore we were not able to control the level of difficulty across conditions (see Kroger et al., 2002). This concern is minimized, however, by the fact that the VLSM results revealed a double dissociation between brain structures contributing to relational-reasoning and visual-match problems, and the pattern of results was consistent with language-based vs. visually-based solutions to the problems, respectively. That is, it seems unlikely that differential difficulty between the conditions would have given rise to such dissociable brain regions. Another caveat is that the current study could not rule out the possibility that the left temporal regions associated with RCPM performance are critical for reasoning itself, rather than being a language zone that indirectly affects reasoning. That is, multiple processes such as language and relational reasoning may be dependent on distinct but overlapping networks in the middle and superior temporal gyri. Further studies are needed to tease apart these possibilities.

It should also be noted that our study did not allow us to test the role of the right hemisphere, nor very anterior and posterior portions of the left hemisphere, because our sample included predominantly left hemisphere, middle cerebral artery patients. A recent VLSM analysis of the Wechsler Adult Intelligence Scale found that the Matrix Reasoning subtest was associated with lesions in the right temporal lobe (Glascher et al., 2009), although perceptual vs. reasoning-based items were not distinguished. Functional imaging and lesion studies have also suggested that relational reasoning is dependent in part on anterior portions of prefrontal cortex (e.g., Bunge, Wendelken, Badre, & Wagner, 2005; Christoff et al., 2001; Crone et al., 2009; Kroger et al., 2002; Waltz et al., 1999), but these regions were not sufficiently represented in our sample. Nonetheless, our dataset allowed us to test and support our main hypothesis that relational reasoning relies on language processing centers in the left temporal lobe.

In summary, the current study showed that patients with compromised language ability were impaired on the Raven's Colored Progressive Matrices test, specifically on items requiring relational reasoning. Regions in the left middle and superior temporal gyrus were most critical to performance on the reasoning items, while inferior temporo-occipital regions were most critical to performance on visual-match items. In conjunction with previous studies, these data provide further support for the idea that language plays a critical role in humans' ability to solve complex reasoning problems.

Acknowledgments

This research was supported in part by the Department of Veterans Affairs, NIH/NINDS 5 P01 NS040813, and NIH/NIDCD 5 R01 DC00216. We would like to thank Carter Wendelken and William Prinzmetal for their helpful comments on this manuscript. We would also like to thank Robert Knight for his assistance with the lesion reconstructions. Last, we are indebted to the enthusiastic participants who took part in this study.

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