

Differentiating lexical form, meaning, and structure in the neural language system

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A technique for studying the relationship between brain and language, which involves correlating scores on two continuous variables, signal intensity across the entire brains of brain-damaged patients and behavioral priming scores, was used to investigate a central issue in cognitive neuroscience: Are the components of the neural language system organized as a single undifferentiated process, or do they respond differentially to different types of linguistic structure? Differences in lexical structure, in the form of the regular and irregular past tense, have proven to be critical in this debate by contrasting a highly predictable rule-like process (e.g., jump-jumped) with an unpredictable idiosyncratic process typified by the irregulars (e.g., think-thought). The key issue raised by these contrasts is whether processing regular and irregular past tense forms differentially engages different aspects of the neural language system or whether they are processed within a single system that distinguishes between them purely on the basis of phonological and semantic differences. The correlational analyses provide clear evidence for a functional differentiation between different brain regions associated with the processing of lexical form, meaning, and morphological structure.

morphology | neuroscience

Evidence from neuropsychology and neuroimaging has broadly delineated the neural language systems involved in language function as involving an extensive fronto-temporal network that, depending on the modality involved, is more or less strongly left lateralized (1). A central issue in cognitive neuroscience is whether these systems are organized as a single undifferentiated process or whether they respond preferentially to different types of linguistic input (2–6). The distinction between the regular and irregular English past tense plays a key role in this debate because it provides a strong contrast between a highly predictable rule-like regular process (e.g., jump-jumped) and an unpredictable idiosyncratic process typified by the irregulars (e.g., teach-taught). The critical issue is whether processing regular and irregular past tense forms differentially engages different aspects of the neural language system or whether morphological structure can be captured solely on the basis of phonological and semantic relationships (3). Current evidence, derived primarily from lesion-deficit studies, has not proved to be decisive, and the issue continues to be hotly debated (3, 5).

Neuropsychological studies show that dissociations in performance on the regular and irregular past tense are associated with different regions of cortical damage. Poor performance on the regulars with sparing of the irregulars is reliably associated with damage to the left inferior frontal gyrus (2, 6, 7), whereas poor performance on the irregulars in the presence of good performance on the regulars is associated with a less consistent pattern of damage. Although some patients with left anterior temporal lobe damage after either semantic dementia or herpes simplex encephalitis have problems with the irregulars (7, 8), damage in this region does not invariably produce irregular past tense deficits (9), and patients with irregular past tense deficits do not always have temporal lobe damage (10). Although these dissociations seem to provide evidence for neural differentiation, they can also be inter-

preted as consistent with single-mechanism accounts. On such accounts, problems with the regulars stem from a general phonological deficit, whereas problems with the irregulars are causally related to a semantic deficit (11), so that these apparent morphological dissociations do not reflect actual differences in the neural representation of morphological structure. However, inconsistent with this reinterpretation, some patients who have disproportionate difficulties with the regulars do not have a generalized phonological deficit (12), whereas patients with a deficit for the irregulars do not always have a semantic deficit (10). Conversely, patients with a semantic deficit do not always have accompanying problems with the irregular past tense (9).

The main source of evidence in this currently inconclusive debate has come from neuropsychological patients and, thus, critically depends on the accurate localization of cortical lesions that can then be related to patterns of behavior. As such, it potentially suffers from the known weaknesses of the classical lesion-deficit approach. These weaknesses concern the methods used to assess both cortical damage and behavioral deficits. The methods used to assess cortical damage are typically based on the assumption that there is a binary distinction between intact and damaged tissue. Although a variety of different methods are used to determine the extent of a patient's lesion, involving either manual tracing of the lesion or more automated methods (13–18), the purpose of the procedure is the same: to judge whether cortical tissue is damaged or intact. This judgment typically involves an all-or-none distinction between intact and damaged tissue that fails to capture a potentially much larger range of informative variation in the degree of cortical damage. A second limitation of this general approach is that the analysis is usually confined to specific brain regions, with regions of interest determined on the basis of lesion locations, rather than covering the entire brain. This type of analysis reduces the probability of determining the properties of the overall functional network (19, 20).

All of these problems can be significantly mitigated by using voxel-based whole-brain methods of the type used here, which assign a continuous signal intensity value to each voxel, thus providing a more sensitive estimate of degree of tissue integrity. Because these analyses cover the whole brain (21, 22) they escape the limitations of analyses that are limited to specific brain regions and can form the basis for a more comprehensive understanding of the neural system involved in any cognitive task, including language function. Moreover, they have the potential to identify suboptimal tissue in sites that are remote from the original insult. These sites may not have been directly damaged but may have become dysfunctional by being disconnected from other important sites in the network, as in diaschisis (23).

Many lesion-deficit studies also suffer from significant limitations by virtue of the procedures they employ to assess a patient's behavioral deficit. Again, these procedures typically involve a

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binary decision as to whether a patient has an impairment on the basis of a set of behavioral scores (24). The patient's performance is judged as being either impaired or intact, which is inevitably a coarse-grained estimate of the actual degree of impairment. The method used here assesses behavioral deficits in a more graded manner by obtaining continuous behavioral data and correlating this information with the continuous intensity value for each voxel across the brain. This method increases both the sensitivity and the statistical power of the analyses. Using this approach, we have recently shown its sensitivity to different components of a complex cognitive task (22).

In this study, we used this approach to investigate the properties of the neural system underpinning spoken language processing. Our question was whether different aspects of language function differentially engage different aspects of the cortical network involved in language processing. To address this question, we asked whether processing regularly and irregularly inflected past tense forms differentially involves distinct regions of the neural network for language. To this end, we correlated the signal intensity of each voxel, across the whole brains of 22 right-handed brain-damaged patients, with these patients' behavioral scores on a priming study that tested their ability to process the phonological form, meaning, and morphological structure of spoken words. In this behavioral task (described in detail in ref. 7), patients heard prime-target pairs of words and nonwords and made a lexical decision to the second (target) stimulus in each pair. The critical contrasts involved sets of word pairs that were either morphologically related, contrasting regularly inflected past tense forms (e.g., jumped-jump) and irregularly inflected past tense forms (slept-sleep) or related only in phonological form (e.g., pillow-pill) or in meaning (e.g., card-paper). Across two testing sessions, a target word was either preceded by a related word (as in the examples above) or an unrelated word. By comparing lexical decision responses to targets in the related and unrelated conditions, we obtained a proportion priming score for each of the four conditions for each patient, which was entered into the correlational analysis.

This set of experimental conditions enables us to test the main predictions of single and dual mechanism models of past tense processing. Single mechanism accounts claim that deficits for the regulars are due to a general phonological processing deficit. This claim requires that patients who have problems with the regular past tense will also have phonological deficits (11). This hypothesis leads to the prediction that variation in performance on the regulars and on the phonologically related forms should be associated with damage to the same cortical regions. Although we have argued on the basis of behavioral data from brain-damaged patients that this hypothesis is incorrect (12), the finding that performance on the regular past tense and on phonologically related pairs correlate with damage to different cortical regions would be compelling new evidence against a single-mechanism account.

Similarly, single-mechanism accounts claim that problems with the irregular past tense arise from a semantic impairment, leading to the prediction that variations in priming for the irregulars and for the semantically related pairs should be associated with damage to the same neural tissue. In contrast, accounts not committed to a single route would not predict these associations between performance and brain damage. Instead, they predict that performance on the regulars and irregulars will be correlated with signal intensity in different cortical regions, and neither will necessarily overlap with those cortical regions associated with semantic or phonological processing.

Materials and Methods

Subjects. The subjects were 22 brain-damaged patients (ages 25–78 years; mean 52; SD 15) with predominantly left-lateralized brain damage. Table 1, which is published as supporting information on the PNAS web site, provides details of the patients, including the main lesion site as conventionally defined. Note that these lesion

descriptions do not include areas of subthreshold damage, which will nonetheless be relevant to the whole-brain correlational analysis. The average duration postonset of their insult was 6.5 years. All were right-handed native speakers of English and were members of our long-term pool of neuropsychological patients. Scores on a variety of basic neuropsychological tests showed that they were not significantly cognitively impaired (e.g., mean Ravens score = 32, max = 36). Patients were included in the study if they had (i) a T1 weighted 3D MRI scan and (ii) could reliably perform the lexical decision task. They were not selected on the basis of either their lesion location or their pattern of behavioral scores.

Behavioral Study: Materials and Procedure. Stimuli in the two morphological conditions consisted of 42 prime-target regular past tense pairs (e.g., turned-turn; forced-force) and 42 irregular past tense pairs (e.g., began-begin; fed-feed). The primes were inflected, and the targets were uninflected stem forms. We also included a third condition in which primes and targets were phonologically but not semantically or morphologically related (e.g., tent-ten; clamp-clam) and a fourth condition in which pairs were simple words that were semantically but neither phonologically nor morphologically related (e.g., coast-shore; chief-boss). There were 24 items in each of these latter two conditions. Each prime word was matched to a control word in frequency and number of syllables (see ref. 9 for further details). In addition to the 132 test pairs, we included 80 real word fillers (a mixture of nouns and verbs), making a total of 212 real words and 212 legal nonwords. Two versions of the materials were constructed so that the target word only occurred once per version. Stimuli were recorded by a native speaker of British English, digitized at 22 kHz with markers placed at the acoustic onset of each target word. The markers served to trigger a timing device that measured the subject's reaction time to the target word. Subjects heard prime-target pairs and were asked to make a lexical decision to the target by pressing a response key. All patients were tested on both versions of the materials, with an interval of at least 1 month between each testing session.

For each subject, each data point was inverse transformed, and the mean for each condition was calculated. The use of inverse transformations deals with outliers without the need to remove data reaction times points (26). We then calculated a proportion priming effect [by dividing the difference between the unrelated and related prime reaction times (RTs) by the unrelated prime RT] for each of the four conditions. This calculation minimized the effect of overall RT differences across the patients. These values were used in the correlational analyses. The proportion priming effects for each patient in each experimental condition are given in Table 2, which is published as supporting information on the PNAS web site, together with the mean proportion priming effects for a group of seven healthy control volunteers (ages between 56–69 years) for comparison purposes (see ref. 7).

Healthy subjects show a robust pattern of priming for both regularly and irregularly inflected word pairs and for semantically related pairs but no significant priming for words that are merely phonologically similar (7). Five percent of the patients showed this normal pattern, with 45% showing abnormal priming in one condition, 23% in two conditions and 9% in three conditions (see Table 2).

Imaging Analyses. Preprocessing. The T1 images were preprocessed in SPM99 (Wellcome Institute of Cognitive Neurology, London) by spatially normalizing them to the Montreal Neurological Institute template, skull stripping, and smoothing. Spatial normalization is necessary to achieve anatomical correspondence across all images before statistical analysis. The spatial normalization algorithm in SPM99 minimizes differences in brain position, size, and shape between image and template, utilizing the residual sum of squared differences as the matching criterion. We calculated the optimum 12-parameter linear affine transformation (i.e., translations, rota-

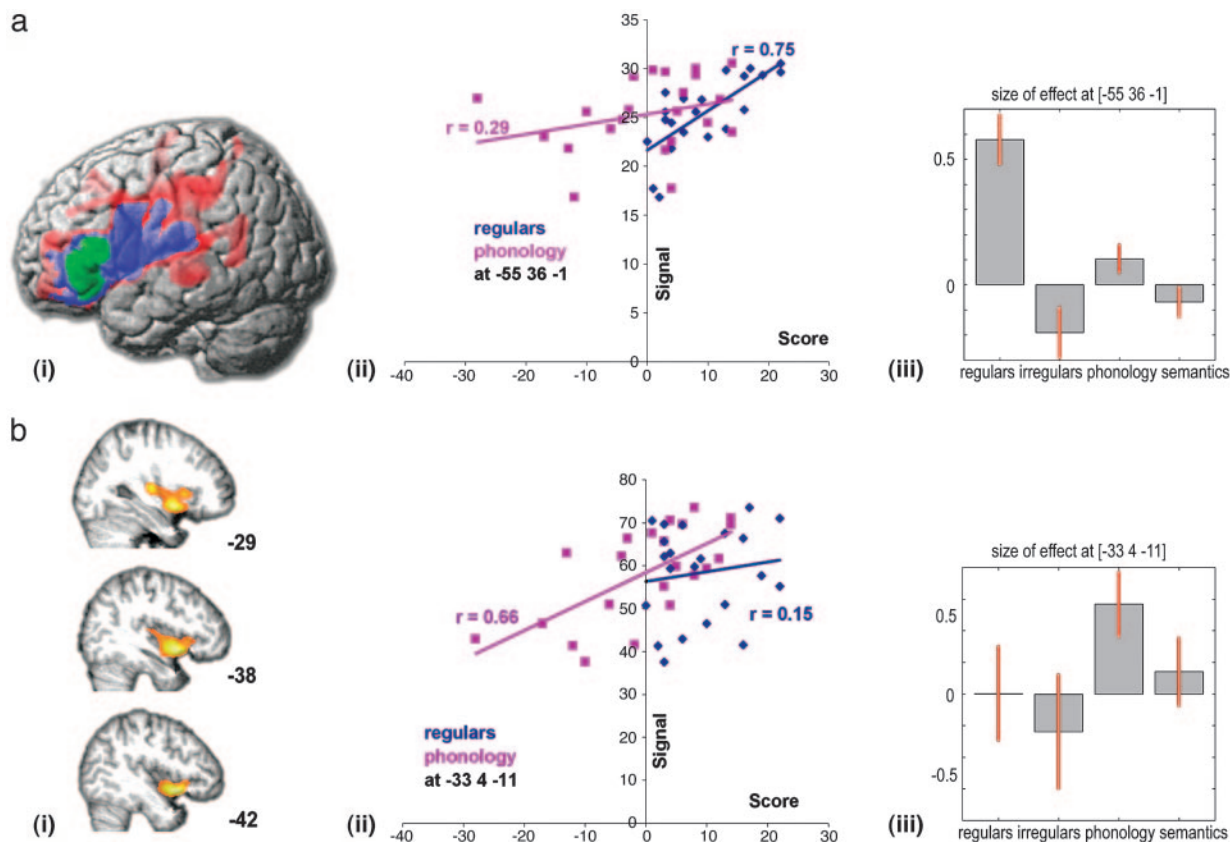


Fig. 1. Areas that correlate with priming for regularly inflected and phonologically related conditions. (a) Cortical regions that correlated with priming for regularly inflected verbs at different voxel level thresholds of $P < 0.001$ (green), $P < 0.01$ (blue), and $P < 0.05$ (red) are shown on a 3D rendered spatially normalized brain. Clusters survived correction at $P < 0.05$ cluster level adjusted for the entire brain. The statistical peak $(-55, 36, -1)$ is in the left inferior frontal gyrus (BA47), and the cluster extends superiorly into BA 45. At lower thresholds, the cluster extends from Broca's to Wernicke's areas and includes the arcuate fasciculus. The scatter plots (ii) and correlation coefficients show the relationship between the filtered signal (adjusted for global mean) and the behavioral scores at the most significant voxel $(-55, 36, -1)$. The bar chart (iii) shows effect sizes (and SE) for all four experimental conditions at the same peak voxel. (b) Sagittal slices (i) of the mean patient spatially normalized T1 weighted image showing correlations with phonological priming at $P < 0.05$ voxel level. The cluster includes most of the insula shown in Talairach x values in mm. The scatter plot and correlation coefficients (ii) show the relationship between the filtered signal and behavioral scores at the most significant voxel $(-33, 4, -11)$. The bar chart (iii) shows effect sizes (and SE) for all four experimental conditions at the same peak voxel.

tions, zooms, and shears in x , y , and z directions) between the image and the template and corrected for the global nonlinear shape differences with nonlinear warping, modeled by a linear combination of smooth spatial basis functions ($7 \times 8 \times 7$ in this instance) (27). Although spatial normalization can be compromised by the presence of large lesions, this problem can usually be resolved by using weighting in the form of masks to exclude the lesion during nonlinear normalization (28) or by penalizing unlikely deformations (27). We found that by using regularization to constrain the nonlinear part of the algorithm and effectively penalizing unlikely deformations associated with the presence of lesions increased the accuracy of the process. The spatially normalized images were visually compared with the Montreal Neurological Institute template to assess normalization accuracy. There was no post hoc evidence of artifactual distortion. The images were then skull stripped by masking each one with the standard SPM99 brain mask and smoothed with a 10 mm Gaussian kernel to increase the signal to noise ratio (29) to account for small-scale variations in individuals' sulcal and gyral anatomy and to render the data more normally distributed (by the central limit theorem).

Statistical analysis. The normalized, skull stripped, and smoothed images were analyzed by using the framework of the general linear model (30) as implemented in SPM99. We correlated four behavioral measures for each patient with signal intensity in each voxel across all of the scans (22). To normalize for global signal variation, we

included the global mean voxel value for each scan as a confounding covariate. Patient age was also included in the analysis as a confounding covariate. We used linear regression models and tested regional effects for each of the behavioral measures by using T statistics. Gaussian random field theory was used to correct for the search volume in terms of P values (31). The four behavioral measures used in the analyses were proportion priming scores for the regular, irregular, phonologically related, and semantically related conditions.

For the correlational analyses, we followed two complementary analysis strategies. First, we constructed two multiple linear regression models, one correlating signal intensity with priming scores from the regular and phonological conditions and the other focusing on the irregular and semantic conditions. These analyses enabled us to test directly the key competing hypotheses, on the one hand about the relationship between the regulars and phonology and the cortical regions with which they are associated and, on the other hand, about the relationship between the irregulars and semantics. Second, to evaluate these binary contrasts in the context of the overall pattern of effects, we included the priming scores from all four conditions in a third model. From this analysis, we obtained estimates of the effect of each of the four behavioral measures in those regions that correlated with behavioral scores in the two main models. These effect size plots (which are equivalent to regression coefficients) are shown in Figs. 1 and 2 together with

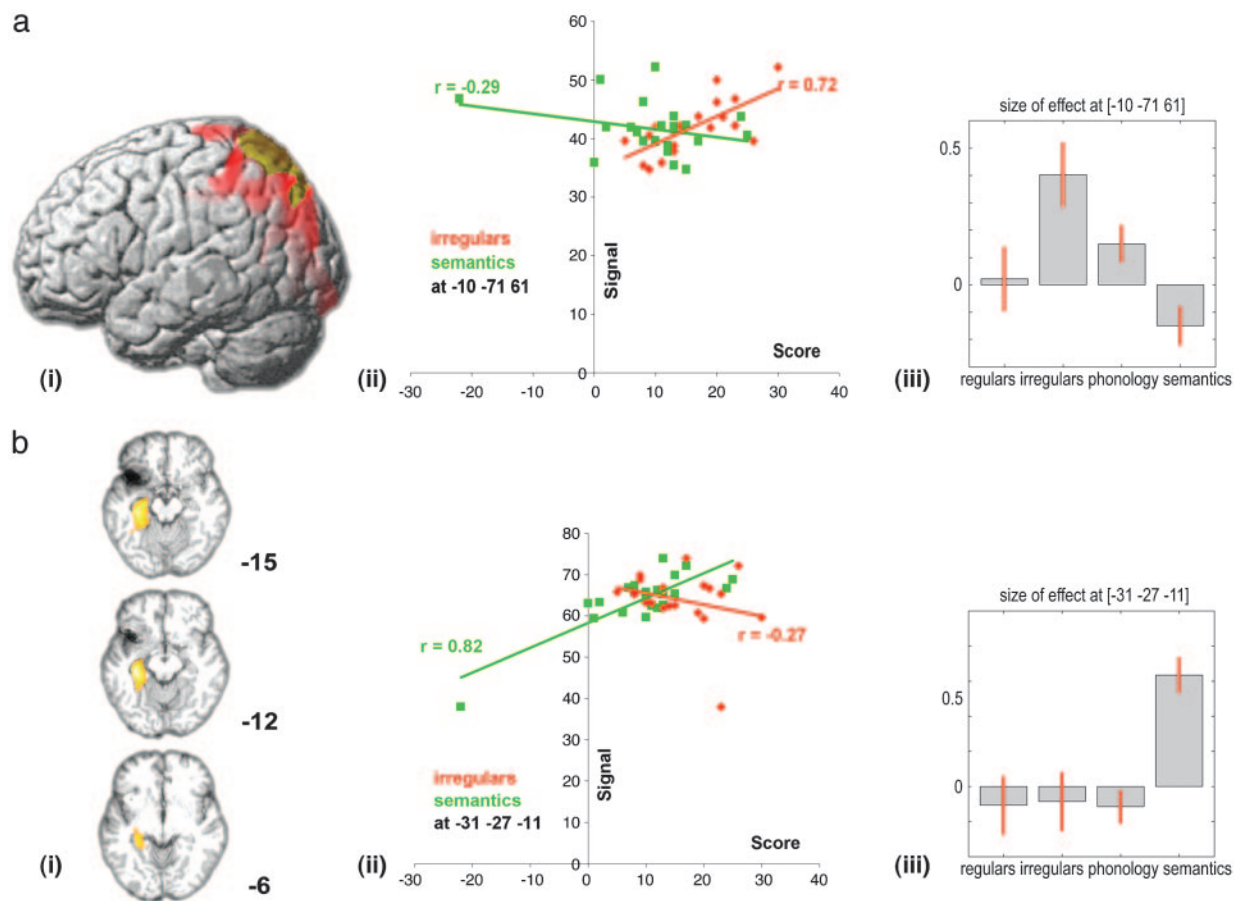


Fig. 2. Areas that correlate with priming for irregularly inflected and semantically related conditions. (*a*) Cortical areas that correlated with priming for irregularly inflected verbs at voxel level thresholds of $P < 0.01$ (yellow) and $P < 0.05$ (red) are shown on a 3D rendered spatially normalized brain. Cluster, which survived correction at $P < 0.05$ cluster level, is adjusted for the entire brain and is located in the L superior parietal lobule; at the lower threshold, it includes the inferior parietal lobule and angular gyrus. The scatter plots and correlation coefficients (*ii*) show the relationship between filtered signal and the behavioral scores at the most significant voxel ($-10, -71, 61$). The bar chart (*iii*) shows effect sizes (and SE) for all four experimental conditions at the same peak voxel. (*b*) Cortical areas that correlated with priming for the semantically related condition are shown on axial slices of the spatially normalized mean patient T1 weighted image thresholded at voxel level $P < 0.001$. The cluster shown survived a random field corrected P value of $P < 0.05$, adjusted for the entire brain. The cluster included the L medial fusiform (BA37) and the hippocampus and surrounding parahippocampal regions (BA 28, 35, and 36) and, at a lower threshold, also included the L middle temporal gyrus (BA 22). Talairach z values are shown in mm, and $L = L$. The scatter plot and correlation coefficients (*ii*) show the relationship between filtered signal and the behavioral scores at the most significant voxel ($-31, -27, -11$). The bar chart (*iii*) shows effect sizes (and SE) for all four experimental conditions at the same peak voxel.

the results of the two paired analyses. The two-condition and four-condition analyses produced very similar outcomes.

Priming scores were entered into each linear regression model as independent variables, and signal intensity from each voxel in the images was treated as the dependent variable. Each of the models revealed the cortical regions in which there was a significant correlation between signal intensity and behavioral scores for the experimental conditions. Coordinates of the peak significant voxels are reported in Montreal Neurological Institute space; these coordinates are reported as Talairach and Tournoux labels after correction for differences between the Talairach and the Montreal Neurological Institute stereotactic coordinate systems (32). We threshold the statistical parametric maps at the standard threshold of $P < 0.001$, uncorrected at the voxel level, and report maxima for clusters that survive a random field corrected P value of < 0.05 , adjusted for the entire brain. When there are no significant results at this conservative threshold we report results from a lower threshold and report these values with their levels of significance.

In each of the models comparing regulars with phonology and the irregulars with semantics, we plotted the filtered signal (i.e., after adjustment for global mean) against the priming scores for both conditions at the most significant voxel for each condition (as

identified from the SPM analysis). We extracted the filtered signal by using the Marsbar region of interest toolbox (33). We calculated correlation coefficients and tested for significant differences between them by using Williams' (1959) test (34) for significant differences between dependent correlations.

Results

The direct contrast between the regulars and phonology showed that priming effects for the regulars correlated significantly with signal intensity in the left inferior frontal gyrus, with the maxima at Brodmann's area (BA) 47 ($-55, 36, -1$), extending superiorly into BA 45 ($-58, 24, 11$). At a slightly more liberal threshold ($P < 0.01$ voxel level), a more extensive region of the LH significantly correlated with performance on the regulars. This region included the left superior temporal gyrus, extending posteriorly from primary auditory cortex into the anterior extent of Wernicke's area (BA 41, 42) and anteriorly along the left superior temporal gyrus. When the threshold was lowered still further ($P < 0.05$ voxel level), the cluster now encompassed all of Wernicke's area, looping around to include the arcuate fasciculus and including BAs 47, 44, and 45 (Broca's area) (Fig. 1*ai*).

These data closely correspond to the classical Broca-Wernicke-Lichtheim model of language function, where the white matter tract

of the arcuate fasciculus connects superior temporal and inferior frontal regions in a neural language system and to the dorsal route identified in more recent neural accounts of the language system (e.g., ref. 1). The correlation between signal intensity in this region and performance on the regulars supports previous claims that damage to this dorsal route impairs the ability to process regularly inflected past tense forms (2, 35). These areas are clearly not critical for phonological processing *per se*. We see this dissociation both in Fig. 1*aii* and in the regions that correlate with phonological priming (Fig. 1*bi*). Fig. 1*aii* shows that there is a significant correlation ($r = 0.75$, $P < 0.01$) between the regulars and signal in this region (plotted at the peak voxel for this correlation) but not between phonological scores and signal intensity ($r = 0.29$; ns). Williams' test, which compares the two correlations, shows that they are statistically different [$t(19) = 2.290$, P (two-tailed) = 0.033]. Fig. 1*aiii*, derived from the four-condition model, plots the effect size for each of the four conditions at the same peak voxel and demonstrates that only the regulars show a strong relationship between priming score and signal intensity.

Scores in the phonological condition did not correlate with any specific cortical regions at the standard threshold ($P < 0.001$ voxel, $P < 0.05$ cluster levels). A more lenient significance level of $P < 0.01$ (voxel level) produced a significant cluster that included most of the insula (peak at $-33, 3, -11$) and extended anterolaterally to the left inferior frontal gyrus (BA47, peak at $-43, 10, -10$) inferiorly to BA44 and 45 (see Fig. 1*bi*). This finding is consistent with previous functional imaging studies that have implicated the insula in phonological processing during language comprehension (36, 37) and production (38). Fig. 1*bii* shows the significant correlation between the scores for the phonological condition and signal in the insula ($r = 0.66$, $P < 0.01$). There was no correlation between scores in the regular condition and signal intensity in this region ($r = 0.15$). Williams' test showed that the two correlations were significantly different [$t(19) = 2.295$, P (two-tailed) = 0.033]. Fig. 1*biii* shows the size of the effect for all four conditions at the relevant peak voxel, confirming that only scores in the phonological condition were related to signal intensity in this region. The results shown in Fig. 1 clearly show that there is very little overlap between the cortical regions involved in the priming relationship for regularly inflected words and phonologically related words.

The critical issue here is that these phonological priming effects (primarily interference rather than facilitation) reflect a breakdown in the patients' ability to handle phonologically related forms, correlating with damage to areas known to be important in aspects of phonological processing. A key point for single-mechanism accounts is whether this breakdown in phonological processing capacity is linked to deficits in processing regularly inflected forms as well. We do not see this pattern behaviorally (with no correlation between proportion priming for regulars and the phonology condition) nor do we see it in the correlations with cortical areas for the two conditions. This result is inconsistent with the single-mechanism claim for the underlying phonological nature of the functional and neural substrate for the processing of regularly inflected forms.

Turning to the second set of comparisons (see Fig. 2), the direct contrast between the irregulars and semantics showed that priming for irregularly inflected forms correlated with signal intensity in markedly different regions to those which correlated with semantic priming. Irregular priming correlated with voxels in the L superior parietal lobule at $P < 0.01$ (voxel level) and, at a lower threshold of $P < 0.05$ (voxel level), the inferior parietal lobule and angular gyrus (Fig. 2*ai*). These regions have been associated with irregular past tense processing in previous neuroimaging studies (39, 40) and are typically activated in lexical processing tasks (41, 42). Their role in lexical processing is supported by the finding that damage to these regions, which often accompanies lesions in Wernicke's area, results in the speech comprehension deficits typical of Wernicke's aphasia (43, 44). Wernicke's area and the surrounding parietal

regions are thought to be involved in the mapping between spoken forms and their meanings.

In contrast, scores in the semantic priming condition significantly correlated with cortical tissue damage in L temporal regions (Fig. 2*bi*). More specifically, the regions correlating ($P < 0.001$ voxel, $P < 0.05$ cluster levels) with semantic priming included the L medial fusiform (peak at $-31, -36, -17$; BA37) and the hippocampus (peak at $-31, -27, -11$) and surrounding parahippocampal regions (BA 28, 35, and 36). These regions are typically thought to be involved in semantic processing (41, 45, 46). At a lower threshold ($P < 0.01$ voxel, $P < 0.05$ cluster levels) the L middle temporal gyrus was also implicated. The L middle temporal gyrus is the region most activated in semantic priming tasks involving spoken words and, so, the most comparable to the study used here (47, 48).

This difference between the regions that are associated with priming for semantically related and irregularly inflected words is clearly revealed in the plots shown in Fig. 2*aii* and *bii*. Fig. 2*aii* shows that there is a significant correlation ($r = 0.72$, $P < 0.01$) between the scores for the irregular condition and signal intensity at the peak voxel for the irregular effects but no correlation between semantic priming and signal intensity in this region ($r = -0.29$). The two correlations differ significantly [$t(19) = 4.094$, P (two-tailed) < 0.001]. Similarly, Fig. 2*bii* shows a significant correlation ($r = 0.82$, $P < 0.01$) between the scores for the semantic condition and signal at the peak voxel for the semantic effects but no correlation between irregular priming and signal intensity in the same region ($r = -0.27$). The two correlations again differ significantly [$t(19) = 4.941$, P (two-tailed) < 0.001]. In confirmation of these contrasts, the effect size plots in Figs. 2*aiii* show that only priming scores for the irregulars had a significant effect in the cortical region that correlated with irregular priming scores, whereas the plots in Fig. 2*biii* show that only the semantic condition had a significant effect in the cortical regions that correlated with semantic priming scores.

Finally, a comparison of Figs. 1*a* and 2*a* show that processing of irregularly inflected forms was not correlated with the regions implicated in regular past tense processing. We did not find any correlations between behavioral scores on the irregulars and damage to the regions that correlated with priming for the regulars, even at a lower threshold of $P < 0.01$ (voxel level), or when allowing for small volume correction for multiple comparisons. Similar analyses for the regulars on those regions associated with irregular past tense processing also failed to show any effects.

Discussion

These results show that correlating signal intensity with continuous behavioral data obtained from manipulations of specific lexical functions is strikingly sensitive to different components of language processing, with a relatively small number of subjects, and demonstrates the possibility of obtaining meaningful correlations between brain and behavior without making *a priori* assumptions about either behavioral deficit or lesion location. The advantage of using continuous measures is that they increase the range of data that are entered into the correlation, and this fact may account for the degree of sensitivity and selectivity shown here.

Taken together, these results show that the cortical regions that correlate with processing different aspects of spoken words, their internal structure, form, and meaning, encompass an extensive left hemisphere language system involving frontal, temporal, and parietal regions. This finding is consistent with the earliest neuropsychological models that proposed that the neural network for language function included the left inferior frontal cortex, the superior and middle temporal cortex, and the posterior superior temporal cortex. In addition, these regions were claimed to be interconnected through the arcuate fasciculus, which links posterior superior temporal regions with the inferior frontal cortex. The present results provide evidence both for the engagement of the components of this network in language processing and for functional differentiation within the network.

Processing regularly inflected forms is strongly associated with a connected network of L superior-temporal-frontal sites, whereas this system is less critically involved in processing irregularly inflected forms. Damage to these regions has a profound impact on processing regularly inflected words but does not seem to affect the processing of irregularly inflected words. This difference demonstrates the modulation of the language system as a function of the processes underpinning regular and irregular past tense morphology.

The lack of overlap in the cortical sites involved either in phonological and regular past tense processing, or in irregular and semantic processing, argues strongly against connectionist claims that problems with the regular and irregular past tense are reducible to phonological or semantic deficits. These claims predict overlap between the cortical regions involved. Contrary to these predictions, the direct contrast between the regulars and phonology and between the irregulars and semantics, even when we lower the threshold, reveals no overlap in the regions associated with these different aspects of linguistic performance. These results cannot be dismissed on the same grounds that proponents of single-mechanism accounts have dismissed earlier functional imaging studies (39, 40) that found differences in the neural regions associated with regular and irregular past tense processing. These studies were based on the assumption that single-mechanism accounts predict that activation patterns should not differ for regular and irregular past tense forms. When differences were found, they were interpreted as evidence against single-mechanism accounts. In fact, single-mechanism accounts do not require that there should be no neural differences in the processing of regular and irregularly inflected forms (49), because they may differ on a number of dimensions other than the way in which their past tense is formed. For Seidenberg and Arnoldussen (49), the critical test is whether the processing of regularly inflected forms patterns with phonological processing, whereas irregularly inflected forms pattern with semantic processing. The current study directly tests this claim and finds that it is not supported.

The correlational data presented here are, instead, consistent with claims that processing regular and irregular inflectional morphology in English engages different aspects of the cortical lan-

guage system (39, 25). In particular, it has recently been claimed that the dorsal speech processing route, which involves the left superior temporal gyrus, Wernicke's area, and connections through the arcuate fasciculus to the left inferior frontal cortex, is involved in morphophonological parsing processes that segment morphologically complex spoken forms into stems and affixes. Regular past tense forms, which have the overt structure of a stem plus affix, preferentially engage this dorsal route. These procedures do not apply to irregular past tense forms, which do not have this overt structure. Instead, the irregular past tense forms have stored lexical representations that can be disrupted if brain damage either affects these representations directly or disrupts the mechanisms involved in the process of mapping from phonology to semantics (35). A similar suggestion has recently been proposed (10) on the basis of data from an amonic patient who had problems with the irregulars. Miozzo suggests that this patient, typical of amonic patients in general, has impairments in lexical processing as evidenced by her difficulty in retrieving a word's phonology. On the hypothesis that irregular past tense forms must be accessed as whole forms, so that alternative access routes involving decompositional mechanisms cannot be invoked, problems in accessing stored lexical representations should differentially disadvantage the irregulars compared with the regulars.

A particular strength of the approach described here is that the differential pattern of correlations derives from an analysis involving the same brains and sets of behavioral scores reflecting manipulations of specific linguistic variables in the same task. The results cannot be explained away in terms of confounds because of different patients tested on different tasks or variability in the ability of patients to perform a task. The results of this study enable us to distinguish between competing cognitive accounts of the structure of the language system by providing evidence against a single mechanism account that differentiates between regularly and irregularly inflected words purely on the basis of phonology and semantics and in support of significant, linguistically relevant functional differentiation within the language system.

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