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Research report

Phonological dyslexia and dysgraphia: Cognitive mechanisms and neural substrates

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ABSTRACT

To examine the validity of different theoretical assumptions about the neuropsychological mechanisms and lesion correlates of phonological dyslexia and dysgraphia, we studied written and spoken language performance in a large cohort of patients with focal damage to perisylvian cortical regions implicated in phonological processing. Despite considerable variation in accuracy for both words and non-words, the majority of participants demonstrated the increased lexicality effects in reading and spelling that are considered the hallmark features of phonological dyslexia and dysgraphia. Increased lexicality effects were also documented in spoken language tasks such as oral repetition, and patients performed poorly on a battery of phonological tests that did not involve an orthographic component. Furthermore, a composite measure of general phonological ability was strongly predictive of both reading and spelling accuracy, and we obtained evidence that the continuum of severity that characterized the written language disorder of our patients was attributable to an underlying continuum of phonological impairment. Although patients demonstrated qualitatively similar deficits across measures of written and spoken language processing, there were quantitative differences in levels of performance reflecting task difficulty effects. Spelling was more severely affected than reading by the reduction in phonological capacity and this differential vulnerability accounted for occasional disparities between patterns of impairment on the two written language tasks. Our findings suggest that phonological dyslexia and dysgraphia in patients with perisylvian lesions are manifestations of a central or modality-independent phonological deficit rather than the result of damage to cognitive components dedicated to reading or spelling. Our results also provide empirical support for shared-components models of written language processing, according to which the same central cognitive systems support both reading and spelling. Lesion–deficit correlations indicated that phonological dyslexia and dysgraphia may be produced by damage to a variety of perisylvian cortical regions, consistent with distributed network models of phonological processing.

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1. Introduction

Phonological dyslexia and dysgraphia are written language disorders characterized by a disproportionate difficulty in processing non-words compared to real words, giving rise to an exaggerated lexicality effect in reading and spelling (Beauvois and Dérouesné, 1979; Dérouesné and Beauvois, 1979; Coltheart, 1996; Shallice, 1981; Roeltgen et al., 1983; Henry et al., 2007). Within the framework of dual-route models (Ellis, 1982; Patterson and Shewell, 1987; Ellis and Young, 1988; Shallice, 1988; Coltheart et al., 2001), these syndromes have been interpreted to reflect the selective breakdown of sublexical phoneme–grapheme conversion mechanisms with relative preservation of lexical–semantic procedures for reading and spelling. By contrast, proponents of connectionist models maintain that phonological dyslexia and dysgraphia are not actually caused by damage to cognitive components dedicated to written language processing but instead reflect the disruption of the phonological representations involved in speech production/perception (Plaut et al., 1996; Patterson et al., 1996; Farah et al., 1996; Patterson and Lambon Ralph, 1999; Harm and Seidenberg, 1999, 2001; Crisp and Lambon Ralph, 2006; Welbourne and Lambon Ralph, 2007). According to this view, the written and spoken language deficits documented in these patients have a common origin and are merely different manifestations of the same underlying central or modality-independent phonological impairment. The phonological deficit hypothesis is supported by observations that many individuals with phonological dyslexia/dysgraphia also show prominent impairments and increased lexicality effects on phonological tasks that do not involve reading or spelling (e.g., repetition, rhyme judgment/production, phoneme segmentation and blending) (Shallice, 1981; Patterson and Marcel, 1992; Patterson et al., 1996; Berndt et al., 1996; Friedman, 1995, 1996a; Farah et al., 1996; Crisp and Lambon Ralph, 2006; Fiez et al., 2006; Jefferies et al., 2007). Note, however, that to date only a single study conducted formal assessments of the strength of the association between general phonological impairment and reading performance in a group of patients with phonological dyslexia (Crisp and Lambon Ralph, 2006), and there have been no systematic attempts to explore the relationship between phonological ability and spelling performance in patients with phonological dysgraphia. Furthermore, there are also isolated reports of patients with phonological dyslexia/dysgraphia who apparently did not show significant impairments on non-orthographic tests of phonological processing (Dérouesné and Beauvois, 1985; Bisiacchi et al., 1989; Caccappolo-van Vliet et al., 2004a, 2004b; Tree and Kay, 2006) and these cases have been cited as evidence against the phonological deficit hypothesis (Coltheart, 1996, 2006).

Besides the continuing dispute about the universality and causal role of the proposed central phonological deficit, our current understanding of the cognitive mechanisms and neural substrates of phonological dyslexia/dysgraphia is subject to some additional limitations. Amongst these is the fact that most of the relevant neuropsychological evidence comes from single case reports or small group studies that used different language assessment tasks, making comparisons across patients problematic and raising questions about the general implications of the findings. Furthermore, many previous studies have focused exclusively or primarily on either reading or spelling performance and, overall, researches have paid considerably more attention to phonological dyslexia than to phonological dysgraphia. As an unfortunate consequence of this extreme ''modular'' approach, it is often difficult to appreciate the nature of the functional relationship between the two written language disorders. The frequency and reliability of associations versus dissociations between phonological dyslexia and dysgraphia is of central importance to the ongoing controversy about whether reading and spelling rely on shared or independent cognitive systems (for a review, see Tainturier and Rapp, 2001), and the resolution of this debate would clearly benefit from additional empirical data bearing on this issue.

With respect to neural substrates, it should be pointed out that the vast majority of published studies on phonological dyslexia and dysgraphia have provided insufficient information about lesion location thereby reducing the power and accuracy of lesion–deficit correlations. Although there appears to be an association between phonological dyslexia/dysgraphia and damage to perisylvian cortical regions implicated in phonological processing, attempts to determine the critical lesion site have produced inconsistent and contradictory results. For instance, it has been suggested that posterior perisylvian lesions centering on the supramarginal gyrus may be the critical neural substrate of phonological dysgraphia (Roeltgen et al., 1983; Roeltgen and Heilman, 1984). However, this syndrome has also been described in patients with damage limited to anterior perisylvian cortical regions, including the frontal operculum/precentral gyrus and insula (Marien et al., 2001; Rapcsak and Beeson, 2002; Henry et al., 2007). Similarly, it has been proposed that damage to the frontal operculum played a central role in the pathogenesis of phonological dyslexia (Fiez and Petersen, 1998; Fiez et al., 2006), but there are also reports of patients with lesions confined to posterior perisylvian cortex (for a review, see Lambon Ralph and Graham, 2000). Thus, lesion–deficit correlations to date have failed to identify a single cortical area essential for sublexical reading and spelling, leading some investigators to propose that phonological dyslexia and dysgraphia may be caused by damage to a number of perisylvian cortical regions that are components of a distributed neural network dedicated to phonological processing (Alexander et al., 1992; Rapcsak and Beeson, 2002; Henry et al., 2007). The distributed nature of phonological processing is supported by functional imaging studies in normal individuals that typically reveal activation in multiple functionally linked perisylvian cortical regions during speech production/perception and phonological awareness tasks (for reviews, see Binder and Price, 2001; Vigneau et al., 2006). Of special note is the fact that these perisylvian cortical regions are also activated during reading and spelling tasks, providing additional demonstration that spoken and written language performance rely on shared phonological representations (Jobard et al., 2003; Price et al., 2003; Mechelli et al., 2003, 2005; Price and Mechelli, 2005; Beeson et al., 2003; Beeson and Rapcsak, 2003; Omura et al., 2004; Norton et al., 2007).

The investigation reported here was designed to fill some of the gaps in our understanding of the neuropsychological

mechanisms and lesion correlates of phonological dyslexia and dysgraphia by providing a detailed description of written and spoken language performance in a large cohort of patients with well-defined focal lesions involving perisylvian cortex. Our specific aims were to establish whether damage to perisylvian language areas consistently produced the profile of phonological dyslexia and dysgraphia and to explore the extent to which measures of general phonological ability predicted reading and spelling performance in these patients. A closely related objective for our study was to document associations as well as theoretically important dissociations between phonological dyslexia and dysgraphia, both at the group and at the individual level, and thereby determine whether damage to perisylvian cortical regions implicated in phonological processing had similar consequences for reading and spelling. Finally, we wanted to conduct a detailed analysis of the lesion correlates of phonological dyslexia/dysgraphia to ascertain whether damage to specific perisylvian cortical regions played a pre-eminent role in producing the characteristic reading/spelling profile or whether the neuroanatomical data are more consistent with distributed network models of phonological processing.

Unlike in most previous studies, patients were selected for inclusion based on lesion criteria (i.e., the presence of damage to perisylvian cortex) rather than behavioral criteria (i.e., the presence of phonological dyslexia or dysgraphia). While the symptom-based approach adopted by the majority of investigators can demonstrate that a particular type of written language impairment is associated with damage to a specific cortical region, it is equally important to determine whether damage to the same cortical region reliably produces the characteristic behavioral deficit (cf. Hillis et al., 2004). For instance, it may be that most patients with phonological dyslexia/dysgraphia have perisylvian damage but that only a relatively small proportion of patients with perisylvian lesions demonstrate this type of reading and spelling impairment. A lesion-based approach avoids the potential pitfall of excluding patients who do not show the expected clinical profile and is therefore more likely to capture the full spectrum of written language impairment associated with damage to a given cortical region. As such, the method is less susceptible to selection artifact resulting from the inclusion of only those individuals who show an unusually large discrepancy between word and non-word reading or spelling scores that may not be representative of the population of patients with similar lesion characteristics. To our knowledge, this type of lesion-based approach was only used in two previous studies of phonological dyslexia/dysgraphia: one that investigated reading performance and phonological processing in a group of patients ($n = 11$) with lesions centered on the frontal operculum (Fiez et al., 2006), and another that examined spelling performance in patients ($n = 13$) with damage to a variety of perisylvian cortical structures (Henry et al., 2007). In addition to identifying the cognitive mechanisms and neural substrates of both phonological dyslexia and dysgraphia in the same large cohort of patients, in the current investigation we also attempted to correlate damage to specific perisylvian cortical regions with various behavioral measures of reading and spelling performance. We expected that the lesion–deficit correlations obtained in our study might also be useful for validating the results of neuroimaging studies of reading/spelling and phonological processing in normal individuals. This type of converging evidence is particularly important because imaging studies alone cannot determine with certainty the functional role of a cortical region in language processing or even prove that an activated region is *necessary* for normal performance. Conclusive evidence that a cortical area is critical for a specific language task requires demonstrations that damage to the region produces the expected behavioral deficit (Price and Friston, 2002; Price et al., 2003).

2. Methods

2.1. Participants

To determine eligibility, we reviewed behavioral and neuroimaging data from left-hemisphere damaged patients with language impairment who were evaluated in the Aphasia Research Project at the University of Arizona over the last 5 years. To be included, participants had to fulfill the following selection criteria: (1) CT or MRI evidence of damage to one or more perisylvian cortical regions implicated in phonological processing, including posterior inferior frontal gyrus/Broca's area (BA44/45), precentral gyrus (BA4/6), insula, superior temporal gyrus/Wernicke's area (BA22), and supramarginal gyrus (BA40), and (2) having received a detailed evaluation of reading and spelling performance in the subacute or chronic stage of their illness (typically several months or years post-onset). Using these dual criteria, we were able to identify 31 participants for the study (mean age = 60.07 years, range: 40–78; average years of education = 14.55, range: 11–20). Lesion etiology was ischemic/hemorrhagic stroke in 30 cases, whereas one patient sustained perisylvian damage due to surgical excision of a tumor. The perisylvian patient cohort included individuals with a range of aphasia subtypes and severities, as measured by the Western Aphasia Battery (Kertesz, 1982). The mean Aphasia Quotient (AQ) for the group was 67.87 (SD = 25.80). Aphasia profiles included Broca's ($n = 9$), conduction ($n = 4$), Wernicke's ($n = 2$), anomic ($n = 10$) and global ($n = 1$). Five individuals obtained scores in the non-aphasic range. Information about spelling performance for a subgroup of 13 patients had been presented in a previous report (Henry et al., 2007). Control data for the experimental measures of written and spoken language processing was available from a group of 31 healthy individuals (mean age = 63.71, range: 39–81; average years of education = 15.52, range: 12–18) tested in our laboratory over the same 5-year period. The perisylvian patient and control groups did not significantly differ with respect to age [$t(60) = -1.476$, $p = .145$] or education [$t(60) = -1.672$, $p = .100$].

2.2. Assessment of written language functions

For all patients and controls, oral reading and spelling to dictation scores were derived from lists containing 40 regular words, 40 irregular words, and 20 non-words. Due to some changes in our test battery over the period of time covered by this review, three different word lists and two different non-word lists had been administered to participants. Although some of the real word items differed across the lists,

there was considerable overlap with 41 words appearing on all three lists and another 38 occurring on two of the three lists. Regular and irregular words on each list were balanced for frequency (Baayen et al., 1995), imageability (Coltheart, 1981; Cortese and Fugett, 2004), and length. Formal analyses indicated that there were no significant differences across the three lists with respect to these variables [frequency: $F(2,237) = 1.808$, $p = .166$; imageability: $F(2,237) = .004$, $p = .996$; and length: $F(2,237) = .654$, $p = .521$]. Regular words were characterized by common or high-probability phoneme–grapheme mappings (e.g., grill), whereas irregular words contained at least one uncommon or low-probability mapping (e.g., choir). Non-word stimuli were derived from real words by changing some of the letters while maintaining orthographic and phonological plausibility (e.g., nace) and were balanced with the word lists for length. The items on the two non-word lists were similar in length and orthographic/phonological complexity.

2.3. Oral repetition and tests of phonological ability

To determine whether participants demonstrated a lexicality effect in spoken language tasks, we compared oral repetition performance for 20 real words and 20 non-words from the reading/spelling lists. In scoring repetition performance, phonologically accurate reproductions of the target word/non-word item were accepted as correct, but patients were not penalized for minor sound distortions resulting from impaired neuromuscular execution/articulatory implementation (i.e., dysarthria). Repetition scores were available for all 31 perisylvian patients and for 17 control subjects. In addition, a subset of 25 patients and 17 controls were evaluated with a phonological battery that required the identification, maintenance, and manipulation of sublexical phonological information but did not involve reading or spelling. The battery consisted of six non-orthographic tests of phonological ability: rhyme judgments, rhyme production, phoneme segmentation, deletion, blending, and replacement. In the rhyme judgment task, individuals had to decide whether pairs of words spoken by the examiner rhymed (e.g., bear – chair). Seven patients and five control subjects received a pilot version of the phonological battery that included 10 word pairs for rhyme judgments, whereas the other participants received a 40-item version of the auditory rhyme judgment task from the Psycholinguistic Assessments of Language Processing in Aphasia (PALPA, subtest #15) (Kay et al., 1992). In the rhyme production task, participants were asked to produce a word that rhymed with the target stimulus presented by the examiner ($n = 10$). In the phoneme segmentation task, participants were presented with a target stimulus spoken by the examiner and were asked to produce the initial ($n = 10$) or final ($n = 10$) phoneme of the word (e.g., pet – /p/). For phoneme deletion, participants had to delete the initial ($n = 5$) or final ($n = 5$) phonemes of target words and produce what remained (e.g., beach – each). In the phoneme blending task, participants were presented with individual phonemes spoken by the examiner and were asked to combine the phonological elements and produce the word ($n = 10$) (e.g., /k/ /ae/ /t/ – cat). Finally, the phoneme replacement task required substitution of the initial ($n = 5$) or final ($n = 5$) phoneme of a word with another phoneme provided by the examiner (e.g., block – clock). Percent correct performance on all six subtests of the phonological battery was computed individually and then averaged to derive a phonological composite (PC) score for each participant.

2.4. Lesion analyses

For 12 participants, information about lesion location was only available from clinical CT ($n = 6$) or MRI ($n = 6$) scans. For the remaining 19 patients, in addition to the clinical scans, we also obtained high resolution T1-weighted research MRI scans on a 3T GE scanner using a 3D inversion recovery (IR) prepped spoiled-gradient-echo sequence (SPGR) with voxel dimensions of $1 \times 1 \times 1.5$ mm. Spatial normalization of research scans into common stereotactic space was performed using SPM2 software (Wellcome Department of Cognitive Neurology, University College, London, UK). Lesions were masked during alignment in order to minimize the contribution of abnormal brain tissue to the normalization process (Brett et al., 2001).

To allow for comparisons between clinical and research scans, all lesions were manually mapped onto the standard single-subject brain template in MRIcro (Rorden and Brett, 2000). For patients with research scans, the lesions were mapped on 15 axial slices with 5 mm gaps encompassing the entire perisylvian region (slices 55–125). For patients with clinical CT/MRI scans, the lesions were mapped by locating the appropriate axial slices after carefully aligning the template image with the angle of the scan. Following lesion reconstruction, a determination was made as to the presence or absence of damage to five perisylvian cortical regions of interest (ROIs), including posterior inferior frontal gyrus/Broca's area (pars opercularis/triangularis, BA44/45), precentral gyrus (BA4/6), insula, superior temporal gyrus/Wernicke's area (BA22), and supramarginal gyrus (BA40). These perisylvian ROIs have well-established roles in phonological processing, as revealed by clinical studies of aphasic patients (Nadeau, 2000; Blumstein, 2001; Burton and Small, 2002; Hickok and Poeppel, 2000, 2004) and by functional imaging studies in normal individuals (Binder and Price, 2001; Vigneau et al., 2006). Furthermore, the ROIs encompassed all the perisylvian cortical regions that showed activation in imaging studies of reading and spelling in neurologically intact participants (Jobard et al., 2003; Price et al., 2003; Mechelli et al., 2003; Price and Mechelli, 2005; Mechelli et al., 2005; Beeson et al., 2003; Beeson and Rapcsak, 2003; Omura et al., 2004; Norton et al., 2007). Damage to individual perisylvian ROIs was determined by superimposing the reconstructed lesions on the gyral (AAL) maps in MRIcro, as well as by identifying the areas involved both on the template brain and on the original scans with reference to salient neuroanatomical landmarks and standard brain atlases (Damasio and Damasio, 1989; Damasio, 1995).

3. Results

Four perisylvian patients with severe speech production impairment performed extremely poorly even on the relatively easy task of repeating familiar words and they produced few recognizable responses on all other language tests requiring spoken output. Consequently, oral reading, repetition, and

phonological battery scores for these individuals were excluded. As a result, the analyses reported here were based on written spelling data from all 31 perisylvian patients, oral reading and repetition data from 27 patients, of which a subset of 22 completed the full phonological battery. Reading and spelling data were available for all 31 controls, and repetition and phonological battery scores for a subset of 17 participants.

3.1. *The influence of stimulus type: evidence for increased lexicality effects in reading and spelling*

Reading and spelling accuracy for regular words, irregular words, and non-words is shown in Fig. 1. A 2 (group) × 3 (stimulus type: regular, irregular, non-word) repeated measures ANOVA conducted on the reading scores revealed main effects of group [$F(1,56) = 49.542$, $p < .0001$], stimulus type [$F(2,112) = 60.093$, $p < .0001$], and a group × stimulus type interaction [$F(2,112) = 51.050$, $p < .0001$]. Planned contrasts with Bonferroni corrections for multiple comparisons ($\alpha = .0045$) indicated that perisylvian patients read regular words [$t(56) = -4.263$, $p < .0001$], irregular words [$t(56) = -4.587$, $p < .0001$], and non-words [$t(56) = -10.300$, $p < .0001$] worse than controls. Within-group comparisons revealed that in patients with perisylvian lesions non-word reading was significantly impaired compared to both regular word [$t(26) = -7.492$, $p < .0001$] and irregular word reading [$t(26) = -6.799$, $p < .0001$], whereas there were no differences in reading accuracy for the latter two stimulus categories [$t(26) = 1.411$, $p = .170$]. No differences were found in reading performance for regular words, irregular words, and non-words in normal controls. Overall, real word reading was substantially better than non-word reading in patients with perisylvian lesions [$t(26) = 7.202$, $p < .0001$], whereas the lexical status of the stimuli did not have a significant effect on reading performance in normal controls.

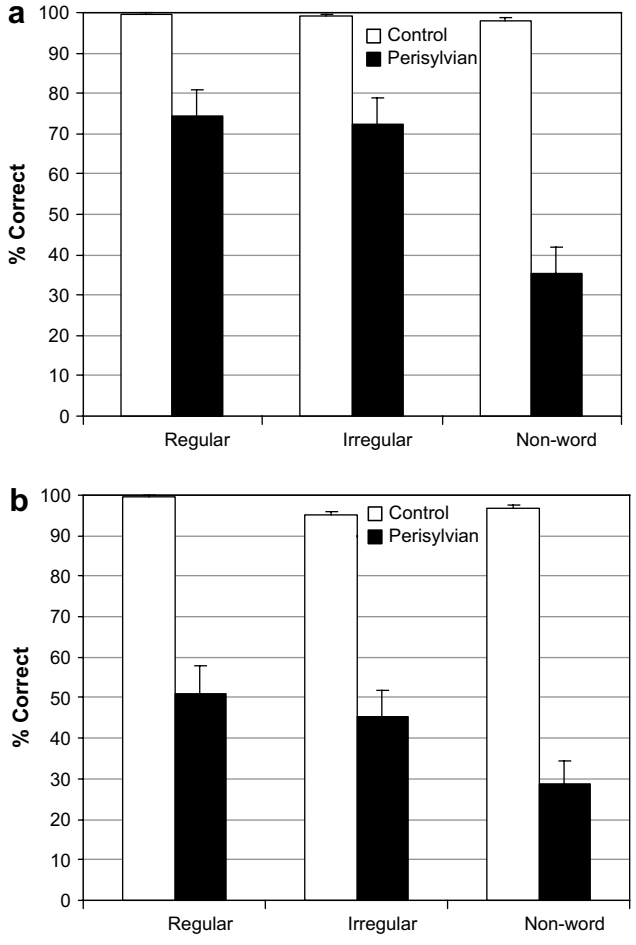

Fig. 1 – a and b. The influence of stimulus type on reading (a) and spelling (b) performance in perisylvian patients and normal controls.

A 2 (group) × 3 (stimulus type: regular, irregular, non-word) repeated measures ANOVA conducted on the spelling scores indicated main effects of group [$F(1,60) = 82.089$, $p < .0001$], stimulus type [$F(2,120) = 24.115$, $p < .0001$], and a group × stimulus type interaction [$F(2,120) = 18.429$, $p < .0001$]. Planned contrasts with significance levels adjusted for multiple comparisons revealed that perisylvian patients spelled regular words [$t(60) = -6.901$, $p < .0001$], irregular words [$t(60) = -7.516$, $p < .0001$], and non-words [$t(60) = -11.976$, $p < .0001$] worse than controls. Within-group comparisons indicated that in patients with perisylvian lesions non-word spelling was significantly impaired compared to both regular word [$t(30) = -5.398$, $p < .0001$] and irregular word spelling [$t(30) = -3.936$, $p = .0005$]. In addition, patients showed an advantage in spelling regular words compared to irregular words [$t(30) = 3.650$, $p = .0010$]. In normal controls, non-word spelling was worse than regular word spelling [$t(30) = -3.300$, $p = .0025$], but there were no differences in spelling accuracy for non-words and irregular words. Controls also showed an advantage in spelling regular words compared to irregular words [$t(30) = 6.341$, $p < .0001$]. Overall, patients with perisylvian lesions spelled real words better than non-words [$t(30) = 4.739$, $p < .0001$]. By contrast, although normal controls spelled non-words less accurately than regular words, the overall comparison between spelling performance for real words versus non-words was not statistically significant.

The results of these initial analyses indicated a strong impact of lexicality on reading and spelling accuracy in patients with perisylvian lesions. Although the perisylvian group was impaired compared to controls for all stimulus types, non-word reading and spelling performance were particularly poor. To confirm that the reading and spelling performance of patients with perisylvian lesions were primarily influenced by the lexical status of the stimuli, we compared the size of the lexicality effect (calculated as % correct words – % correct non-words for each participant) and the size of the regularity effect (calculated as % correct regular words – % correct irregular words) in the two experimental groups (Fig. 2). These analyses revealed that the perisylvian group showed an exaggerated lexicality effect in both reading [$t(56) = 7.343$, $p < .0001$] and spelling [$t(60) = 4.547$, $p < .0001$] compared to controls. By contrast, there were no significant differences between the groups with respect to the size of the regularity effect in reading [$t(56) = 1.009$, $p = .3173$] or spelling [$t(60) = .614$, $p = .5417$]. These results confirm that the main variable to influence written language performance in patients with perisylvian lesions is lexicality, consistent with the profile of phonological dyslexia and dysgraphia. Furthermore, the impact of this variable

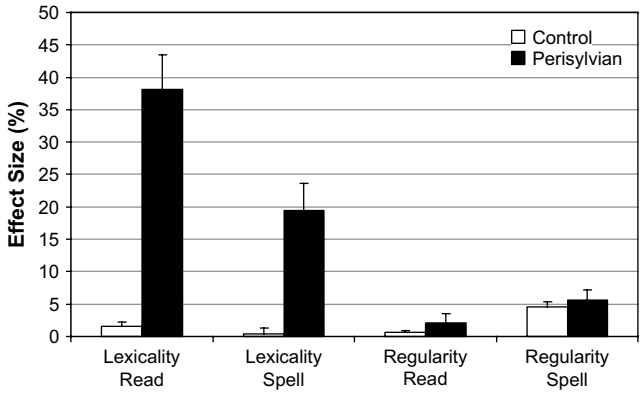

Fig. 2 – Lexicality and regularity effects in reading and spelling for perisylvian patients and controls.

was found to be selective, as the enhanced lexicality effects were unaccompanied by a similar increase in the size of the regularity effect in reading or spelling.

3.2. *The spectrum of written language impairment: evidence for a continuum of severity*

Although the written language performance of the perisylvian group demonstrated the hallmark features of phonological dyslexia and dysgraphia, we also wanted to establish how many individuals actually conformed to this profile and whether there were cases that deviated from this general pattern. To determine the prevalence of phonological dyslexia and dysgraphia in the perisylvian group, we first identified patients who showed lexicality effects >2 SD above the control mean in reading or spelling. However, because of ceiling effects and small variance in the control group (for both words and non-words) we were concerned that this method could potentially produce false positives resulting in an overestimation of the actual number of cases. Therefore, to protect against the possible inflation of the Type I error rate, we conducted a second set of analyses to confirm that patients who fulfilled the first criterion in fact showed statistically reliable differences between real word versus non-word reading and spelling scores (Fisher's exact test).

Based on these dual criteria, we identified 21/27 (77.8%) patients with a profile of phonological dyslexia. The absence of a significant lexicality effect in three other cases (11.1%) was attributable to extremely poor reading performance for both words and non-words (overall accuracy: 0–3%), consistent with global dyslexia, whereas in another two cases (7.4%) it reflected essentially normal performance on our reading lists. Finally, one patient (3.7%) showed an enhanced lexicality effect compared to controls but did not meet our second criterion for a significant impairment in non-word reading. Thus, the vast majority of patients in our group demonstrated a reading profile consistent with phonological dyslexia and the only systematic deviation from this pattern included a few severely impaired individuals with global dyslexia. These findings suggest that the reading impairment of patients with perisylvian lesions is characterized by a continuum of severity ranging from mild phonological dyslexia at one end and global dyslexia at the other.

Similar analyses conducted on spelling scores identified 16/31 (51.6%) patients with the profile of phonological dysgraphia. The absence of a significant lexicality effect was attributable to floor effects in another 11 individuals (35.5%) who were severely impaired in spelling both words and non-words (overall accuracy: 0–8%), consistent with global dysgraphia. Of the remaining four patients (12.9%), one individual demonstrated an enlarged lexicality effect compared to controls but did not meet our second criterion for a significant impairment in non-word spelling, whereas the other three individuals had mild-to-moderate spelling deficits but failed to show an enhanced lexicality effect or a statistically reliable difference in spelling accuracy for real words versus non-words. These findings demonstrate that, as in the case of reading, the spelling impairment of the majority of patients with perisylvian lesions is characterized by a continuum of severity ranging from mild phonological dysgraphia to global dysgraphia. Although phonological dysgraphia is still the dominant pattern, damage to perisylvian cortical regions not infrequently results in profound spelling deficits for both words and non-words.

Taken together, the written language data suggest that although the reading and spelling profiles of patients with perisylvian lesions are *qualitatively* similar, there are *quantitative* differences in levels of performance reflecting the fact that the functional impairment produced by this type of brain damage has more devastating consequences for spelling than for reading (see Fig. 1). We will say more about the differential vulnerability of spelling when we consider the relationship between phonological ability and written language performance in our patients. Here we simply note that our results are consistent with the typical pattern of greater spelling than reading impairment in individuals with central forms of dyslexia and dysgraphia (cf. Tainturier and Rapp, 2001). This general rule seems to apply regardless of written language profiles and therefore independent of whether the damage involves the central phonological, semantic, or orthographic components of reading and spelling (Coltheart et al., 1980; Friedman and Hadley, 1992; Graham et al., 2000; Rapcsak and Beeson, 2004). Consequently, these observations are most likely to reflect an inherent asymmetry between reading and spelling in terms of task difficulty. Spelling is a more difficult task than reading even for normal literate adults (Bosman and Van Orden, 1997; Holmes and Carruthers, 1998; Kessler and Treiman, 2001), and a significant difference between overall spelling versus reading accuracy was also confirmed in our control subjects [$t(30) = -5.904$, $p < .0001$]. Task difficulty effects observed in normal controls are likely to become exaggerated in neurological patients, rendering spelling more vulnerable to the detrimental effects of brain damage in general. A corollary of this asymmetrical relationship between the two written language tasks is that although patients with central dysgraphia may have relatively preserved reading, damage sufficient to produce central dyslexia is typically associated with a more substantial spelling than reading impairment.

Although we used the terms phonological dyslexia/dysgraphia for patients exhibiting a disproportionate impairment of non-word reading and spelling, enhanced lexicality effects are

also characteristic of individuals who receive the diagnostic label of deep dyslexia/dysgraphia (Coltheart et al., 1980; Bub and Kertesz, 1982; Rapcsak, et al., 1991; Crisp and Lambon Ralph, 2006; Jefferies et al., 2007). Phonological and deep dyslexia/dysgraphia were originally considered as separate disorders, but there is now much evidence in favor of the view that the differences between these syndromes are quantitative rather than qualitative in nature. As a result, several investigators have suggested that phonological and deep dyslexia/dysgraphia are more appropriately considered as points along a continuum, with the latter representing a more severe version of the former (Glosser and Friedman, 1990; Friedman, 1996b; Patterson and Lambon Ralph, 1999; Rapcsak and Beeson, 2002; Crisp and Lambon Ralph, 2006). It remains to be determined, however, whether the proposed continuum is best characterized by the severity of the phonological deficit, the degree of semantic impairment, or a combination of both factors (Crisp and Lambon Ralph, 2006; Jefferies et al., 2007). In any event, the continuum hypothesis is supported by the overlapping perisylvian lesion profiles of patients with these written language disorders and also by observations that the damage in deep dyslexia/dysgraphia tends to be more extensive than the damage associated with phonological dyslexia/dysgraphia (Lambon Ralph and Graham, 2000; Rapcsak and Beeson, 2002).

Individuals occupying different points along the phonological-deep dyslexia/dysgraphia continuum can demonstrate substantial overlaps in terms of reading and spelling profiles, and attempts to devise specific diagnostic criteria to distinguish between these disorders must be regarded as somewhat artificial (Rapcsak and Beeson, 2000, 2002; Crisp and Lambon Ralph, 2006). Nevertheless, the production of semantic errors is often considered the defining feature of deep dyslexia/dysgraphia (Coltheart et al., 1980). Therefore, we examined the prevalence of semantic errors in our group of perisylvian patients to determine whether we can find evidence of the proposed phonological-deep dyslexia/dysgraphia continuum. The results of these analyses showed that ''pure'' semantic errors were relatively uncommon, accounting for 5.24% of the total errors in reading and 1.09% of the total errors in spelling. Semantic errors were produced by 11 of the 31 (35.5%) participants, although for all but one of these individuals they comprised only a small proportion of their total reading and spelling errors (10% or less). The only patient who produced a substantial number of semantic errors in reading (21 errors or 35.59% of the total) had an extensive left-hemisphere infarction with complete destruction of the entire perisylvian language zone. Non-word reading was completely abolished and real word reading accuracy was also significantly compromised (26.25% correct). This patient also had a profound spelling deficit (overall accuracy = 3%) and produced three semantic errors (3.89% of the total). The hypothesis that semantic errors are typically produced by individuals with substantial reading and spelling impairments was partially supported by negative correlations between overall reading accuracy and the number of semantic errors in reading ($r = -.350$, $p = .0368$, one-tailed), and between overall spelling accuracy and the number of semantic errors in spelling ($r = -.325$, $p = .0374$, one-tailed) for the perisylvian group. The presence of semantic reading and spelling errors in some of the more severely impaired participants in our cohort suggests that the full spectrum of written language disorders in patients with perisylvian lesions follows the proposed severity continuum of phonological → deep → global dyslexia/dysgraphia, with no sharp dividing lines between these diagnostic categories.

3.3. *The functional relationship between phonological dyslexia and dysgraphia*

As noted earlier, whether reading and spelling rely on shared or independent cognitive systems is a contentious issue in neuropsychology (Tainturier and Rapp, 2001; Rapcsak et al., 2007). In general, *associations* between the reading and spelling profiles of neurological patients have been interpreted to support shared-components models of written language processing, whereas *dissociations* are typically regarded as evidence in favor of the independent systems position (Allport and Funnell, 1981; Ellis, 1982; Patterson and Shewell, 1987; Coltheart and Funnell, 1987; Shallice, 1988; Ellis and Young, 1988; Behrmann and Bub, 1992; Tainturier and Rapp, 2001). Theoretically, double dissociations should provide stronger proof of the existence of functionally distinct cognitive modules underlying reading and spelling than single dissociations because the former are less likely to reflect task difficulty effects or resource artifacts resulting from the differential sensitivity of the two written language tasks to neurological damage (cf. Shallice, 1988). Although the logic behind using double dissociations to make inferences about functional architecture has been called into question (Dunn and Kirsner, 2003; Juola and Plunkett, 2000; Plaut, 2003), the fact remains that these types of observations still offer the strongest neuropsychological evidence for the *potential* independence of cognitive systems and they also place constraints on attempts to explain differences in task performance by reference to a single factor or processing resource (Baddeley, 2003).

We have demonstrated that, considered as a group, perisylvian patients exhibited qualitatively similar reading and spelling impairments with a dominant pattern of phonological dyslexia and dysgraphia. However, we also wanted to determine whether individual patients showed complementary reading and spelling profiles or whether we could find evidence of theoretically important dissociations. In particular, discovering evidence of a double dissociation between phonological dyslexia and dysgraphia would provide empirical support for dual-route cognitive models that postulate distinct sublexical phoneme–grapheme conversion mechanisms for reading and spelling (e.g., Ellis, 1982; Patterson and Shewell, 1987; Ellis and Young, 1988). To search for cases demonstrating potential dissociations between phonological dyslexia and dysgraphia, we first identified patients who showed an increased lexicality effect in only one of the two written language tasks. To be considered a true dissociation, however, cases that fulfilled the first criterion also had to show evidence of a statistically significant difference between non-word reading and spelling scores (Fisher's exact test). This second criterion was added because in our view a substantial discrepancy in performance on the critical tasks of non-word reading and spelling should be a prerequisite for any case qualifying as a theoretically meaningful dissociation between phonological

dyslexia and dysgraphia (cf. Shallice, 1988). Adopting this requirement seems prudent in order to prevent misclassifying patients with trivial differences between non-word reading and spelling scores as examples of dissociations.

The results of individual analyses indicated that 11 of the 27 (40.7%) participants for whom we had matching reading and spelling data showed a concordant pattern of phonological dyslexia and dysgraphia, another three (11.1%) patients demonstrated global dyslexia and dysgraphia, whereas one patient (3.7%) did not show an increased lexicality effect in either reading or spelling. With respect to discordant profiles, in seven patients (25.9%) phonological dyslexia was accompanied by global dysgraphia. The absence of a lexicality effect in spelling in these cases was attributable to severely impaired performance for both words and non-words (i.e., floor effects), reflecting the differential vulnerability of spelling alluded to earlier. Although these cases showed a discordant pattern with respect to the lexicality effect, they did not meet criteria for a true dissociation because there were no significant differences between non-word reading and spelling scores. Another five cases (18.5%) with discordant profiles had relatively mild written language deficits, with two patients demonstrating increased lexicality effects in spelling but not in reading and three patients showing the opposite pattern. Importantly, however, only two of these patients showed a statistically reliable difference between non-word reading and spelling performance. These two individuals in fact seemed to demonstrate complementary dissociations: phonological dyslexia without phonological dysgraphia in one case and phonological dysgraphia without phonological dyslexia in the other. An important question to ask is whether these two patients constitute credible evidence of a double dissociation between phonological dyslexia and dysgraphia that would justify the inference that non-word reading and spelling are mediated by independent central processing components dedicated to sublexical phoneme–grapheme conversion. A closer examination of the language performance of these individuals suggested that such a conclusion would be unwarranted. Specifically, in the case of the patient who showed the discordant profile of phonological dyslexia without phonological dysgraphia, an increased lexicality effect in spelling was actually observed compared to controls but the difference between real word and non-word spelling scores only approached significance ($p = .053$). Furthermore, in this case there were good reasons for assuming that the more substantial impairment in non-word reading reflected the additional contribution of a peripheral speech production deficit. This patient had moderately severe apraxia of speech and there is evidence that the greater computational complexity involved in programming novel motor sequences necessary to pronounce unfamiliar non-words can pose disproportionate difficulties for these individuals (Whiteside and Varley, 1998; Levelt and Wheeldon, 1994; Levelt et al., 1999; Duffy, 2005). Dysfunction at the peripheral stage of motor programming or phonetic encoding in this patient may have increased the magnitude of the impairment in non-word reading beyond what was observed in non-word spelling. As a result, the dissociation documented in this case may not be directly relevant to the debate about whether reading and spelling are supported by shared or independent *central* processing components. This leaves a single patient who demonstrated phonological dysgraphia without phonological dyslexia. This individual in fact had normal reading performance for both words (98.75%) and non-words (100%). She also performed well in spelling real words (93.75%) but obtained a non-word spelling score outside the normal range (70%). Although this case meets all our criteria for a genuine dissociation (and also the criteria for a ''classical dissociation'' as originally proposed by Shallice, 1988), the non-word spelling deficit was relatively mild compared to some of the other cases of phonological dysgraphia described in the literature (e.g., Shallice, 1981; Bub and Kertesz, 1982). Note, however, that this single dissociation consisting of worse non-word spelling than reading performance may still be explainable by reference to task difficulty effects and therefore does not constitute sufficient evidence for the existence of separate sublexical processing modules for reading and spelling (cf. Shallice, 1988).

We have devoted considerable space to discussing the frequency and reliability of associations versus dissociations between phonological dyslexia and dysgraphia in our group of patients because of the potential relevance of such empirical observations to the ongoing controversy about whether reading and spelling rely on shared or independent cognitive systems. We could find no compelling evidence of theoretically important double dissociations that would offer support for cognitive models that postulate independent sublexical phoneme–grapheme conversion mechanisms for the two written language tasks (e.g., Ellis, 1982; Patterson and Shewell, 1987; Ellis and Young, 1988). In general, we are much more impressed by the similarities or associations between the reading and spelling profiles of our patients that were evident both at the group and at the individual level than by the rare dissociations that we were able to document. The strength of the close functional relationship between the two written language tasks is illustrated further by significant correlations between non-word reading and spelling scores ($r = .834$, $p < .0001$, one-tailed) and also between real word reading and spelling scores ($r = .768$, $p < .0001$, one-tailed) for the perisylvian group. In conclusion, our findings suggest that the reading and spelling deficits of our patients were caused by damage to a common functional system that supports both tasks, consistent with the predictions of shared-components models of written language processing.

3.4. *Lexicality effects in spoken language tasks and the relationship between general phonological ability and reading/spelling performance*

As discussed previously, the phonological deficit hypothesis asserts that the written language impairments of patients with phonological dyslexia/dysgraphia result from damage to central phonological representations that also support speech production/perception. If this interpretation is correct, then we would expect to find lexicality effects in spoken language tasks that mirror the lexicality effects demonstrated in reading and spelling. To test this prediction, we compared the oral repetition performance of perisylvian patients and controls. A 2 (group) × 2 (words *vs* non-words) repeated measures ANOVA revealed main effects of group [$F(1,42) = 9.939$, $p = .0030$], stimulus type [$F(1,42) = 19.117$, $p < .0001$], and

a group × stimulus type interaction [$F(1,42) = 13.142$, $p = .0008$]. Planned contrasts with Bonferroni corrections for multiple comparisons ($\alpha = .0125$) indicated no differences between the groups in repeating real words [mean = 95.56% *vs* 99.71% correct, $t(42) = -2.025$, $p = .0492$], but patients repeated non-words significantly worse than controls [mean = 82.96% *vs* 98.53% correct, $t(42) = -3.454$, $p = .0013$]. Within group comparisons revealed a significant advantage of real word over non-word repetition in perisylvian patients [$t(26) = 5.137$, $p < .0001$], whereas there were no differences in repetition accuracy for the two stimulus categories in normal controls [$t(16) = 1.725$, $p = .1037$]. The greater sensitivity of perisylvian patients to the lexical status of the stimuli was further confirmed by comparing the size of the lexicality effect in oral repetition (calculated as % correct words − % correct non-words) for the two experimental groups. These analyses revealed that perisylvian patients exhibited a pathologically increased lexicality effect in repetition compared to controls [mean = 12.59% *vs* 1.18%; $t(42) = 3.625$, $p = .0008$].

Our findings confirm that the influence of lexicality is not limited to reading and spelling performance in individuals with phonological dyslexia/dysgraphia and that similar lexicality effects can be demonstrated in spoken language tasks such as oral repetition. These results, and other similar observations from the literature (e.g., Patterson and Marcel, 1992; Patterson et al., 1996; Farah et al., 1996; Crisp and Lambon Ralph, 2006; Jefferies et al., 2007), are consistent with the notion that the reading and spelling impairments in phonological dyslexia/dysgraphia are part of a central or modality-independent phonological deficit that disproportionately affects the processing of unfamiliar phonological patterns, as exemplified by non-word stimuli, across all language tasks. The impact of the central phonological deficit on language performance, however, is strongly modulated by task difficulty effects. For instance, oral repetition is generally considered an easier task than reading or spelling because in the former patients are provided with a precise phonological model of the intended target without the additional need to manipulate sublexical phonological representations and perform orthographic-to-phonological translations (Patterson et al., 1996; Sasanuma et al., 1996; Farah et al., 1996; Crisp and Lambon Ralph, 2006; Jefferies et al., 2007). We have also seen that spelling is a more difficult task than reading. Task difficulty effects were clearly observed in our patients in the expected order of repetition > reading > spelling [overall accuracy for repetition *vs* reading $t(26) = 4.556$, $p = .0001$; repetition *vs* spelling $t(26) = 6.430$, $p < .0001$; and reading *vs* spelling $t(26) = 4.781$, $p < .0001$]. The important point, however, is that although differences in task difficulty had a definite impact both in terms of overall accuracy and the size of the discrepancy between words and non-words, the performance of perisylvian patients on all three language tasks showed qualitative similarities and was characterized by increased lexicality effects compared to normal controls.

Another central postulate of the phonological deficit hypothesis is that non-orthographic measures of phonological processing should correlate with and be predictive of reading and spelling performance in individuals with phonological dyslexia and dysgraphia. To test the validity of this assumption, we examined the relationship between general phonological ability, as reflected by scores on the phonological battery, and written language performance in perisylvian patients. As expected, the phonological composite (PC) scores of patients with perisylvian lesions were significantly lower than those of normal controls [mean = 54.32% *vs* 94.73%; $t(37) = -6.706$, $p < .0001$] providing evidence of a substantial impairment on non-orthographic tasks requiring the identification, maintenance, and manipulation of sublexical phonological information. Furthermore, and consistent with the predictions of the phonological deficit hypothesis, we obtained significant positive correlations in the perisylvian group between PC scores and non-word reading ($r = .664$, $p = .0002$) and spelling scores ($r = .686$, $p = .0001$) and also between PC scores and real word reading ($r = .801$, $p < .0001$) and spelling scores ($r = .779$, $p < .0001$) (all p-values one-tailed). Overall, PC scores proved to be powerful predictors of written language performance, accounting for 66.9% of the variance in reading accuracy [$F(1,20) = 40.397$, $p < .0001$] and 61.0% of the variance in spelling accuracy [$F(1,20) = 31.285$, $p < .0001$]. PC scores also showed the expected positive correlation with both non-word ($r = .454$, $p = .0165$, one-tailed) and real word repetition scores ($r = .518$, $p = .0062$, one-tailed). Taken together, these findings are consistent with the notion that the written and spoken language impairments of patients with perisylvian damage have a common origin and reflect the disruption of central phonological representations. Phonological dyslexia and dysgraphia are merely different manifestations of this modality-independent phonological deficit rather than the result of selective damage to cognitive components specific to reading or spelling.

Additional insight into the impact of central phonological impairment on written language processing is provided by the data summarized in Fig. 3 where we plotted reading and spelling performance for subgroups of patients falling into different quartiles based on the distribution of phonological composite (PC) scores for the perisylvian cohort. These graphs can be conceived of as a set of performance/resource curves (Shallice, 1988) with the "X" axis reflecting the amount of

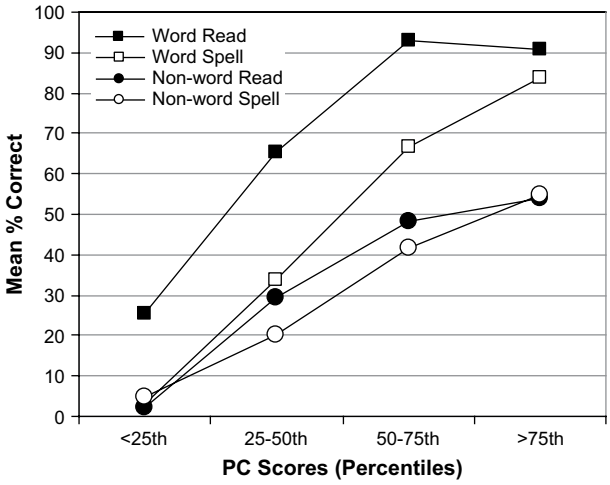

Fig. 3 – The relationship between general phonological ability and reading/spelling performance for words and non-words in patients with perisylvian lesions.

phonological resources available to the different patient subgroups. The critical thing to notice is that the functional impact of reduced phonological capacity on written language performance is strongly influenced both by the lexical status of the stimuli (words *vs* non-words) and by the nature of the task (reading *vs* spelling). With mild-to-moderate reductions in phonological capacity, the disproportionate impairment of non-word reading and spelling results in increased lexicality effects for both written language tasks and patients typically present with the complementary profiles of phonological dyslexia and dysgraphia. With more severe reductions in phonological capacity we still observe increased lexicality effects in reading, but the sharp decline in word spelling ability significantly reduces the size of the lexicality effect until the difference between words and non-words becomes negligible and patients demonstrate equally severe spelling impairments for both types of items. The greater sensitivity of spelling to phonological impairment in these individuals produces the discordant profile of phonological dyslexia with global dysgraphia. Finally, with further reductions in phonological resources the remaining relative advantage of real word over non-word reading is also gradually eliminated and patients exhibit the concordant clinical pattern of global dyslexia and dysgraphia.

The data presented in Fig. 3 suggest that the reading and spelling profiles of perisylvian patients are determined primarily by the severity of the underlying phonological deficit. Specifically, the continuum of reading and spelling impairment documented in these patients seems to be a direct manifestation of, and is largely reducible to, a continuum of central phonological impairment. Differences between the written language profiles of individual patients are quantitative rather than qualitative in nature and reflect the amount of phonological capacity they have lost. Concordant and discordant written language profiles are both explainable by reference to central phonological resource limitations, with the important caveat that reductions in phonological capacity have somewhat different consequences for reading and spelling. As a general rule, spelling is more sensitive to the loss of phonological capacity than reading. Consequently, phonological resource limitations have an asymmetrical impact on the two written language tasks with spelling typically more severely affected than reading for a given level of phonological impairment. This differential vulnerability also means that at the mildest levels of phonological impairment reading could still be relatively normal whereas spelling will already show the characteristic features of phonological dysgraphia. This single dissociation was in fact observed in one of our participants as well as in other patients with phonological dysgraphia due to perisylvian lesions (Shallice, 1981; Bub and Kertesz, 1982; Marien et al., 2001). Our results suggest that the dissociation between impaired non-word spelling and relatively preserved non-word reading in patients with ''isolated'' phonological dysgraphia may arise from relatively mild damage to central phonological representations and need not imply a selective impairment of sublexical phoneme–grapheme conversion procedures dedicated to spelling. In general, based on the task difficulty effects demonstrated in this study, we expect that most patients with phonological dyslexia following perisylvian damage will exhibit either phonological or global dysgraphia, but that not all patients with phonological dysgraphia will show the complementary profile of phonological dyslexia.

3.5. *Lesion–deficit correlations*

We selected participants for this study based on neuroimaging evidence of damage to perisylvian cortical regions involved in speech production/perception and phonological processing in general, including posterior inferior frontal gyrus/Broca's area (BA44/45), precentral gyrus (BA4/6), insula, superior temporal gyrus/Wernicke's area (BA22), and supramarginal gyrus (BA40). As we have shown, damage to these five perisylvian regions of interest (ROIs) in various combinations was reliably associated with the clinical profile of phonological dyslexia and dysgraphia. We also noted that previous attempts to identify the critical lesion site *within* the perisylvian region have produced inconsistent results. This state of affairs may reflect in part the limited availability of precise neuroanatomical information regarding the lesion correlates of phonological dyslexia and dysgraphia in the neuropsychology literature, making it difficult to discern whether a specific cortical region is consistently implicated. Alternatively, the documented variability in lesion sites may be indicative of the fact that phonological processing is not the exclusive domain of any particular perisylvian sub-region but is mediated instead by an integrated network of perisylvian cortical areas that comprise a single functional system. Therefore, damage to several different components of this distributed perisylvian phonological network may be capable of producing the behavioral profile of phonological dyslexia/dysgraphia.

Having access to imaging data collected from a large group of patients with perisylvian damage provided us with an opportunity to test different neuroanatomical models of phonological dyslexia and dysgraphia. The ''critical region'' model implies a unique relationship between the presence/absence of damage to a specific perisylvian ROI and the presence/absence of phonological dyslexia/dysgraphia. Specifically, if damage to a particular perisylvian cortical subdivision is a necessary condition for the occurrence of these written language disorders, then we should find a strong association both between the presence of the behavioral deficit in patients with damage to the ROI *and* the absence of the deficit in patients without damage to the ROI. By contrast, the ''neural network'' model asserts that no single sub-region plays an exclusive role in phonological processing and predicts that damage to different components of the perisylvian cortical network should produce phonological dyslexia/dysgraphia with equal probability. Therefore, we would not expect to discover evidence of a privileged relationship between damage to any particular perisylvian ROI and phonological dyslexia/dysgraphia and should find instead that the occurrence of these written language disorders is largely independent of the location of the damage *within* the perisylvian phonological network.

To determine whether lesions involving specific perisylvian cortical subdivisions had a unique association with phonological dyslexia and dysgraphia, we used a 2×2 chi-square design that tests both the probability of damage to the ROI (present/absent) causing the behavioral deficit and the probability of the deficit (present/absent) being associated with

damage to the ROI (cf. Hillis et al., 2004). Separate analyses conducted for each of the five perisylvian ROIs failed to identify any single cortical area where damage was more likely to be associated with phonological dyslexia or dysgraphia than perisylvian damage that did not involve the ROI. The finding that phonological dyslexia/dysgraphia can be produced by damage to several different perisylvian cortical subdivisions with equal probability, and therefore independent of the location of the lesion within the perisylvian region, is consistent with the predictions of distributed network models of phonological processing.

Although the diagnosis of phonological dyslexia and dysgraphia did not appear to have neuroanatomical specificity within the perisylvian region, we were also interested in determining whether there was a relationship between the lesion status (present/absent) of different perisylvian ROIs and the magnitude of the lexicality effect. Point-biserial correlation tests did not indicate a significant association between damage to any perisylvian ROI and the magnitude of the lexicality effect in spelling, suggesting that the size of the difference between real word and non-word spelling performance was independent of lesion location. By contrast, the size of the lexicality effect in reading correlated with damage to posterior inferior frontal gyrus/Broca's area ($r = .398$, $p = .0393$) and precentral gyrus ($r = .451$, $p = .0173$), suggesting that lesions involving these anterior perisylvian regions produced a particularly large discrepancy between word and non-word reading scores.

To learn more about the relative contribution of different cortical subdivisions, we also compared the written language performance of subgroups of patients whose lesions primarily involved anterior (posterior inferior frontal gyrus/Boca's area, precentral gyrus) versus posterior (superior temporal gyrus/Wernicke's area, supramarginal gyrus) perisylvian ROIs. There were no differences between patients with anterior ($n = 9$) versus posterior ($n = 8$) lesions in non-word (mean = 38.33% *vs* 40.63%) or word (mean = 61.39% *vs* 69.53%) spelling accuracy, or in terms of the size of the lexicality effect (mean = 23.06% *vs* 28.91%). For reading, no differences were found between the anterior ($n = 7$) versus posterior ($n = 7$) subgroups in non-word (mean = 42.14% *vs* 67.86%), or word (mean = 87.14% *vs* 87.86%) reading accuracy but, consistent with the whole group analyses, there was a trend toward patients with anterior perisylvian lesions showing a larger lexicality effect [mean = 45.0% *vs* 20.0%; $t(12) = 2.141$, $p = .0535$].

We also examined whether the total number of perisylvian ROIs involved by the lesions, rather than their specific location, had an influence on the severity of the written language deficit. These analyses indicated significant correlations between the overall extent of damage to the perisylvian cortical network and the severity of the non-word ($r = -.614$, $p < .0001$) and real word ($r = -.580$, $p = .0002$) spelling deficit, and the non-word ($r = -.733$, $p < .0001$) and real word ($r = -.492$, $p = .0041$) reading impairment (all p-values one-tailed). The total number of ROIs involved also correlated with the severity of the phonological impairment, as measured by phonological composite (PC) scores ($r = -.458$, $p = .0154$, one-tailed). Thus, as the number of damaged network components increased, phonological ability became more compromised and written language performance declined for all types of items.

Although all of our patients demonstrated evidence of damage to perisylvian ROIs, the lesions in a number of cases also extended outside the perisylvian language zone. Therefore, we conducted additional analyses to examine the possible contribution of extrasylvian lesion extension to our patients' written language and phonological impairment. Our approach involved creating a mask of the entire perisylvian region in MRIcro and superimposing it on the lesion maps of individual patients to determine the presence or absence of lesion extension outside the perisylvian language zone. Based on this information, we subdivided patients into two groups: the "perisylvian only" group included individuals whose lesions showed no or minimal extension outside the perisylvian region ($n = 13$), whereas the "perisylvian plus" group included participants with evidence of more substantial extrasylvian damage ($n = 18$). Formal comparisons indicated that the "perisylvian plus" group also had more extensive damage to *perisylvian* ROIs (mean number of ROIs involved = 4.056) than the "perisylvian only" group (mean number of ROIs involved = 2.923) [$t(29) = 2.798$, $p = .009$]. Thus, patients in the "perisylvian plus" group had larger lesions overall. Because we have already demonstrated that the total number of perisylvian regions involved significantly correlated with measures of reading/spelling performance and phonological ability (see above), we needed to control for the influence of this variable when comparing groups of patients with versus without evidence of extrasylvian lesion extension. To accomplish this, we conducted a series of ANCOVAs with group ("perisylvian only" *vs* "perisylvian plus") as the factor, non-word and real word reading/spelling scores and PC scores as the dependent variables, and the number of damaged perisylvian regions as the covariate. The results of these analyses indicated that there were no significant differences between the groups on any of the relevant measures of reading/spelling accuracy or phonological ability after controlling for the effect of the extent of the perisylvian damage on performance. Therefore, these findings provided additional evidence that the written language impairment of our patients was primarily attributable to damage to perisylvian ROIs implicated in phonological processing and suggested that the presence of extrasylvian damage did not have a major impact on performance.

We noted earlier that the ROIs selected for this study encompassed the entire network of perisylvian cortical regions that showed activation in functional imaging studies of normal individuals during spoken or written language tasks requiring phonological processing (Binder and Price, 2001; Vigneau et al., 2006; Jobard et al., 2003; Price et al., 2003; Mechelli et al., 2003; Price and Mechelli, 2005; Mechelli et al., 2005; Beeson et al., 2003; Beeson and Rapcsak, 2003; Omura et al., 2004; Norton, et al., 2007). The fact that our patients whose lesions involved various components of this distributed perisylvian cortical network demonstrated evidence of a central or modality-independent phonological deficit, which included phonological dyslexia/dysgraphia among its manifestations, provides strong confirmation of the results of functional imaging studies. In Fig. 4, we provide some examples of the close spatial overlap between the lesions of perisylvian patients with phonological dyslexia/dysgraphia and the cortical areas implicated in phonological processing based on a recent

meta-analysis of neuroimaging studies of language function in normal individuals (Vigneau et al., 2006). As can be seen from Fig. 4, damage to both anterior (posterior inferior frontal gyrus/Broca's area, precentral gyrus) and posterior (superior temporal gyrus/Wernicke's area, supramarginal gyrus) cortical components of the distributed perisylvian phonological network can give rise to phonological dyslexia and dysgraphia.

4. Discussion

In this study we examined the validity of different theoretical claims about the cognitive mechanisms and neural substrates of phonological dyslexia and dysgraphia by conducting a large-scale investigation of written and spoken language function in patients with perisylvian lesions. Using a group-study approach, we were able to address some outstanding issues that have been difficult to resolve based on the extant neuropsychological literature that is heavily dominated by single-case reports. These unsettled questions included the frequency with which perisylvian damage gives rise to phonological dyslexia and dysgraphia, the strength of the association between general phonological impairment and written language performance, the nature of the functional relationship between reading and spelling, and whether damage to specific perisylvian cortical subdivisions played a critical role in producing the characteristic behavioral profile. As expected in any large group study, perisylvian patients demonstrated a wide range of variation in terms of reading and spelling accuracy for both words and non-words. However, the majority of participants showed the increased lexicality effects in reading and spelling that are considered the hallmark features of phonological dyslexia and dysgraphia. The only consistent deviation from this pattern included individuals with global dyslexia/dysgraphia who exhibited severe impairments in processing both words and non-words.

Overall, the behavioral and lesion data obtained in our study provided strong support for the phonological deficit hypothesis of phonological dyslexia/dysgraphia (Patterson and Marcel, 1992; Friedman, 1995, 1996a; Plaut et al., 1996; Farah et al., 1996; Patterson and Lambon Ralph, 1999; Harm and Seidenberg, 1999, 2001; Crisp and Lambon Ralph, 2006; Jefferies et al., 2007). Specifically, the written language disorder of our patients seemed to be just one manifestation of a central or modality-independent phonological impairment rather than the result of damage to cognitive components dedicated to reading or spelling. Consistent with the predictions of the phonological deficit hypothesis, increased lexicality effects were present not only in reading and spelling but also in spoken language tasks such as oral repetition. We also demonstrated that our patients performed poorly on a battery of tasks that required the identification, maintenance, and manipulation of sublexical phonological information but did not involve orthographic processing. Furthermore, a composite measure of general phonological ability was strongly predictive of both reading and spelling performance, and we obtained evidence that the continuum of severity that characterized the written language disorder of our patients was largely attributable to an underlying continuum of phonological impairment.

The proposed general phonological deficit in patients with perisylvian lesions produces enlarged lexicality effects across all language tasks because unfamiliar combinations of

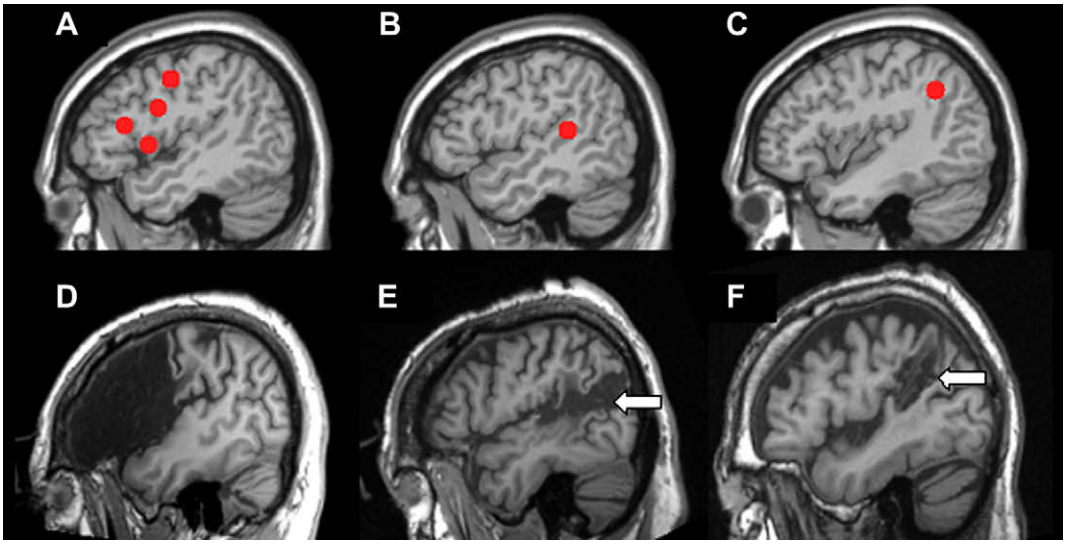

Fig. 4 – The close spatial overlap between the cortical regions that show activation in functional imaging studies of phonological processing in normal individuals and the lesions that produce phonological dyslexia/dysgraphia. Red circles indicate the cortical location of phonological activations derived from the meta-analysis of functional imaging studies of language by Vigneau et al. (2006). Regions were defined by creating 6-mm radius spheres centered on the mean x,y,z coordinates for the activation peaks. A = activations in posterior inferior frontal gyrus/Broca's area and along the precentral gyrus; B and C = activations in superior temporal gyrus/Wernicke's area and supramarginal gyrus. D = Frontal lesion in a patient with phonological dyslexia/dysgraphia involving regions of activation shown in A. E and F = temporo-parietal lesions in patients with phonological dyslexia/dysgraphia involving regions of activation shown in B and C.

phonological elements that make up non-words are more difficult to process and are less stable than familiar phonological patterns that correspond to real words (Patterson and Marcel, 1992; Farah et al., 1996; Patterson et al., 1996; Harm and Seidenberg, 1999, 2001). In addition, unlike non-words, real words receive top-down support from semantic representations. Although the central or modality-independent phonological impairment results in qualitatively similar performance across written and spoken language tasks, there are important quantitative differences attributable to task difficulty effects. As noted by other investigators, oral repetition is the least demanding task in terms of phonological processing requirements and is therefore likely to be associated with the smallest performance deficits (Patterson et al., 1996; Sasanuma et al., 1996; Farah et al., 1996; Crisp and Lambon Ralph, 2006; Jefferies et al., 2007). With respect to written language tasks, our findings indicate that the disruption of central phonological representations has a more devastating impact on spelling than on reading. The differential vulnerability of spelling can result in discordant written language profiles with respect to the lexicality effect, as exemplified by cases of phonological dysgraphia with relatively preserved reading or by patients who show the combination of phonological dyslexia and global dysgraphia. However, we presented evidence that such disparities between reading and spelling performance can arise from damage to a single phonological processing component or computational resource that supports both tasks. The fact that limitations in central phonological capacity provided a satisfactory explanation of both the reading and the spelling impairment of patients with perisylvian lesions, combined with our failure to obtain convincing evidence of a double dissociation between phonological dyslexia and dysgraphia, is consistent with the predictions of shared-components models of written language processing. Note that the phonological deficit hypothesis also provides the most parsimonious account of our patients' general language impairment, since an alternative explanation of increased lexicality effects across spoken and written language tasks would have to postulate the simultaneous breakdown of three independent or task-specific sublexical conversion systems dedicated to repetition, reading, and spelling (cf. Jefferies et al., 2007).

In addition to the behavioral results, the phonological deficit hypothesis is also supported by the lesion profiles of our patients. In particular, we demonstrated that phonological dyslexia and dysgraphia are reliably produced by damage to perisylvian cortical regions implicated in speech production/perception and phonological processing in general by studies of aphasic patients (Nadeau, 2000; Blumstein, 2001; Burton and Small, 2002; Hickok and Poeppel, 2000, 2004) and also by functional imaging studies in normal individuals (Binder and Price, 2001; Vigneau et al., 2006). The close association between perisylvian damage and phonological dyslexia/dysgraphia seems to hold regardless of whether patients are selected based on lesion criteria, as in the current investigation and two other recent reports (Fiez et al., 2006; Henry et al., 2007), or based on behavioral criteria as was typically done in prior studies (for a review of this literature, see Lambon Ralph and Graham, 2000; Rapcsak and Beeson, 2002). While there seems to be a strong reciprocal relationship between perisylvian damage and phonological dyslexia/dysgraphia, our findings suggest that these written language disorders may not have additional localizing value *within* the perisylvian region. Although we are mindful of the dangers associated with drawing inferences from null results, our inability to identify a single critical lesion site responsible for phonological dyslexia/dysgraphia is consistent with the proposal that the different perisylvian cortical subdivisions targeted in our study are components of a common functional system dedicated to phonological processing. The distributed phonological processing system is vulnerable at several different locations and, therefore, damage to different components of this perisylvian cortical network can give rise to phonological dyslexia/dysgraphia with equal probability. Previous attempts to identify the critical lesion site may have produced inconsistent results because no single perisylvian cortical subdivision plays an exclusive role in phonological processing. Note, however, that although in our study damage to different perisylvian regions had a similar propensity for producing phonological dyslexia/dysgraphia, we did obtain some evidence that frontal lesions may result in a particularly large discrepancy between word and non-word reading scores, suggesting that there may be regional differences with respect to the magnitude of the lexicality effect. We also wish to emphasize that although the entire perisylvian neural network participates in processing phonological information in all language tasks, various components of this distributed system may nonetheless make unique contributions and may be differentially important for specific aspects of performance. Therefore, the network conceptualization of phonological processing advocated here does not deny, nor is it inconsistent with, the notion of functional specialization within the perisylvian region. Neuropsychological investigations in aphasic patients and imaging studies in normal individuals have provided evidence that distinct perisylvian cortical regions may be preferentially involved in different components of speech production/perception, including acoustic–phonetic analysis, phoneme discrimination/segmentation, articulatory planning/implementation, auditory–motor integration, and phonological short-term memory (Nadeau, 2000; Blumstein, 2001; Burton and Small, 2002; Boatman, 2004; Scott and Wise, 2004; Hickok and Poeppel, 2000, 2004; Indefrey and Levelt, 2004; Binder and Price, 2001; Vigneau et al., 2006; Fiez et al., 2006). Therefore, different aspects of phonological processing may have been disrupted in our patients as a function of lesion location, suggesting that it might be possible to identify different subtypes of phonological dyslexia/dysgraphia based on the exact nature of the underlying phonological deficit.

The close association between central phonological impairment and defective reading/spelling performance documented in our patients and many other cases of phonological dyslexia/dysgraphia is usually interpreted to support connectionist models of language processing (Plaut et al., 1996; Patterson et al., 1996; Farah et al., 1996; Patterson and Lambon Ralph, 1999; Harm and Seidenberg, 1999, 2001; Crisp and Lambon Ralph, 2006; Welbourne and Lambon Ralph, 2007). However, these findings are also potentially compatible with dual-route models of reading and spelling. Specifically, these models also include phonological processing components that are shared between spoken and written language tasks. For instance, the "phoneme system" and the "phonological lexicon" modules in the interactive dual-route cascaded (DRC) model of

Coltheart et al. (2001) would be involved in all language tasks requiring phonological processing and "lesioning" these components could give rise to the pattern of results obtained in our study. In particular, damage at the level of phoneme units may lead to disproportionate difficulty in processing non-words across all language tasks because phoneme combinations corresponding to familiar words would receive top-down support from the phonological lexicon. Additional damage to phonological lexical representations will produce increasing difficulty with real words, but the lexicality effect would not be abolished except in cases with severe impairment. Thus, damage to phonological processing components in interactive dual-route (Coltheart et al., 2001) or connectionist "triangle" models (Plaut et al., 1996; Harm and Seidenberg, 1999, 2001; Welbourne and Lambon Ralph, 2007) may both be capable of reproducing the spectrum of written and spoken language deficits observed in perisylvian patients with central phonological impairment. Of course, testing these predictions will require fully developed computational models that can both read and spell, as well as perform other language tasks such as repetition, speech production, and comprehension.

We have seen that the phonological deficit hypothesis provides a satisfactory account of phonological dyslexia/dysgraphia in patients with perisylvian lesions who comprise the vast majority of cases described in the literature. Does this necessarily imply that a general phonological impairment will invariably be present in all cases of phonological dyslexia/dysgraphia, as predicted by the strong version of the phonological deficit hypothesis, or can these written language disorders also be produced by damage to non-phonological cognitive components involved in reading and spelling? Phonological dyslexia/dysgraphia *without* phonological impairment finds a natural explanation within the framework of dual-route models that postulate distinct sublexical phoneme–grapheme conversion procedures dedicated to reading and spelling, but it has been suggested that cases demonstrating this type of dissociation might pose a more serious challenge for connectionist models of written language processing (Coltheart, 2006). As noted earlier, there are isolated reports of individuals with phonological dyslexia/dysgraphia who apparently did not demonstrate significant impairments on non-orthographic tests of phonological processing (Dérouesné and Beauvois, 1985; Bisiacchi et al., 1989; Caccappolo-van Vliet et al., 2004a, 2004b; Tree and Kay, 2006). However, the strength of the evidence for the integrity of phonological representations in some of these patients has been called into question and this topic has generated considerable controversy (Coltheart, 1996, 2006; Patterson, 2000; Harm and Seidenberg, 2001; Tree and Kay, 2006; Welbourne and Lambon Ralph, 2007). We suggest that whether patients with the behavioral profile of phonological dyslexia/dysgraphia show evidence of general phonological impairment may depend on the location of the responsible lesions. According to this view, damage to perisylvian cortical regions typically produces phonological dyslexia/dysgraphia in the context of central phonological impairment, whereas cases without phonological impairment will be more likely to have lesions located outside the perisylvian language zone. Along these lines, it is interesting to note that three patients with phonological dyslexia in whom the integrity of phonological representations was established by detailed testing had a diagnosis of Alzheimer's disease (AD) (Caccappolo-van Vliet et al., 2004a, 2004b). The neuropathological changes in AD typically involve extrasylvian temporo-parietal cortical areas with partial sparing of perisylvian regions at least until the later stages of the illness (Braak and Braak, 1996; Thompson et al., 2003), and this neuroanatomical predilection may explain the relative preservation of phonological ability in some of these patients (Bayles and Kaszniak, 1987). In addition, there are reports of phonological dyslexia following focal extrasylvian lesions involving left inferior temporo-occipital cortex, with features of letter-by-letter reading also documented in some cases (Rapcsak et al., 1987; Friedman et al., 1993; Buxbaum and Coslett, 1996). These observations suggest that damage to extrasylvian cortical regions involved in visual/orthographic processing can also potentially give rise to enhanced lexicality effects in written language tasks. Although general phonological ability was not formally assessed in these patients, the anatomical sparing of perisylvian cortical regions suggests that central phonological representations may have been preserved. Because the close association between central phonological deficit and phonological dyslexia/dysgraphia in patients with perisylvian lesions is by now firmly established, we suggest that future studies should focus on patients in whom these written language disorders are encountered in the setting of extrasylvian pathology. Carefully documented dissociations in such individuals between phonological dyslexia/dysgraphia and more general phonological or visual impairment on the one hand, and potential dissociations between reading and spelling performance on the other, could have important implications for theoretical models of written language processing. Such investigations may also help determine whether the strong predominance of cases of phonological dyslexia/dysgraphia with central phonological impairment is related to neurological factors. For instance, the perisylvian cortical regions implicated in phonological processing are supplied by branches of the middle cerebral artery (MCA) and strokes in the territory of this vessel are much more common than strokes affecting the territory of the posterior cerebral artery (PCA) that supplies the inferior temporo-occipital cortical regions involved in visual/orthographic processing (Bogousslavsky and Caplan, 2001).

In closing, we wish to acknowledge certain limitations and interpretive constraints pertaining to our study. Due to the retrospective nature of this investigation, we were unable to ensure that all participants receive testing with the same materials or that they complete all relevant language tasks (e.g., the phonological battery). However, the performance profiles of our patients were similar regardless of the reading/spelling lists used and therefore we do not believe that differences in testing materials influenced our results. It may also be objected to that we used a single criterion (i.e., increased lexicality effect) for diagnosing phonological dyslexia/dysgraphia and did not systematically explore the impact of other relevant linguistic variables known to influence reading/spelling performance in these patients (e.g., imageability). In addition, although we were primarily interested in the role of phonological impairment, it is possible that taking into account measures of semantic ability would have provided a more complete explanation of our patients' written language performance. With respect to lesion–deficit correlations, we

relied on a mix of clinical and research scans which introduced some variability in terms of image quality and detail. Furthermore, most of our patients had damage to multiple perisylvian regions (mean number of ROIs damaged = 3.58) and there were very few cases with lesions confined to a single cortical subdivision. Although in order to learn about the contribution of different perisylvian regions one would ideally want to compare performance across groups of patients with damage restricted to individual ROIs, in practice this may be difficult if not impossible to accomplish since the vascular supply of the brain does not respect the boundaries of cortical subdivisions and damage to multiple regions is the rule rather than the exception in patients with stroke. For the same reasons, it is difficult to find individuals with perisylvian damage whose lesions do not extend outside the strict confines of this cortical zone, and our patients were no exception. However, we did not find evidence that extrasylvian lesion extension played a significant role in our patients' written language impairment. It is also important to emphasize in this context that a full understanding of the cognitive mechanisms and neural substrates of phonological dyslexia/dysgraphia will require direct comparisons of written and spoken language performance between patients with perisylvian damage and patients whose lesions do not involve this region (Henry et al., 2007). Finally, the lesion–deficit correlations used in this study required binary decisions regarding the presence/absence of damage to an ROI and sometimes also about the presence/absence of a behavioral deficit. Such all-or-none distinctions can ignore potentially important information both about the degree of damage to an ROI and also about the degree to which language performance is impaired. By contrast, recent voxel-based lesion-symptom mapping (VLSM) approaches use continuous lesion and behavioral data and therefore do not require patients to be grouped according to lesion site or based on behavioral cut-off scores (Bates et al., 2003; Rorden et al., 2007; Kimberg et al., 2007). The use of these techniques in large groups of aphasic patients with a wide range of focal left-hemisphere lesion sites is likely to provide further insights into the neural correlates of phonological dyslexia/dysgraphia and may identify additional relevant cortical areas that were not explored in our study or may reveal important information about the role of specific cortical subdivisions within the larger ROIs targeted in this investigation.

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