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Deficits in phonology and past-tense morphology: What's the connection?

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Abstract

Neuropsychological dissociations between regular and irregular past tense verb processing have been explained in two ways: (a) separate mechanisms of a rule-governed process for regular verbs and a lexical-associative process for irregular verbs; (b) a single system drawing on phonological and semantic knowledge. The latter account invokes phonological impairment as the basis of poorer performance for regular than irregular past tense forms, due to greater phonological complexity of the regular past. In 10 nonfluent aphasic patients, the apparent disadvantage for the production of regular past tense forms disappeared when phonological complexity was controlled. In a same-different judgment task on spoken words, all patients were impaired at judging regular stem and past-tense verbs like *man/manned* to be different, but equally poor at phonologically matched non-morphological discriminations like *men/mend*. These results indicate a central phonological deficit that is not limited to speech output nor to morphological processing; under such a deficit, distinctions lacking phonological salience, as typified by regular past tense English verbs, become especially vulnerable.

Keywords: Aphasia; Nonfluent; Verbs; Connectionist models

How we learn, represent and produce inflectional morphology is an issue at the heart of psycholinguistic research. One aspect of this issue—how we transform the phonological form of a verb stem into its past tense—has attracted particularly contentious consideration. The controversy raises a debate that applies to many aspects of language processing but will be expressed here with specific reference to past-tense verb processing. According to the dual-mechanism account (Pinker, 1991, 1999), patterns of performance on different verb types require two independent systems: a lexicon from which the stored past-tense form of an irregular verb like *think* is retrieved, and a separate set of rules that transform a regular verb stem like *blink* (or a nonce verb like *hink*) into its non-stored past tense form. According to an alternative view (Rumelhart & McClelland, 1986), performance can be explained in terms of a single integrated system that processes all verbs. These two accounts have been addressed with a variety of sources of evidence: behavioural studies of the speed and accuracy of verb processing in normal adults and children (e.g., Marchman, 1997; Prasada, Pinker, & Snyder, 1990; Seidenberg, 1992; Ullman, 1999); functional imaging and ERP

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studies (Jaeger et al., 1996; Marslen-Wilson & Tyler, 1998; Newman, Izvorski, Davis, Neville, & Ullman, 1999; Penke et al., 1997); studies of developmental disorders (Clahsen & Almazan, 1998; Gopnik & Crago, 1991; Thomas et al., 2001; Ullman & Gopnik, 1999); and adult impairments following brain injury (Marslen-Wilson & Tyler, 1997; Patterson, Lambon Ralph, Hodges, & McClelland, 2001; Ullman et al., 1997). It is this latter form of evidence that will be addressed and expanded in the current paper.

Ullman et al. (1997) reported a neuropsychological double dissociation between regular and irregular past tense performance: In sentence completion and/or single-word reading tasks, patients with fluent aphasia resulting from vascular lesions in posterior left cortical regions and also patients with Alzheimer's disease were better at producing the past-tense forms of regular verbs, whereas patients with nonfluent aphasia from vascular lesions in anterior left cortical regions were more successful at producing the past-tense forms of irregular verbs. This double dissociation is a direct prediction of dual-mechanism theories which propose that these two verb classes are processed by separate mechanisms and brain systems; but the dissociations have also been claimed to be compatible with and predictable from connectionist, single system models (Plaut, 1995; Plunkett & Juola, 1999). The connectionist approach to past-tense production is a development of the original Rumelhart and McClelland (1986) parallel distributed processing (PDP) verb model. In its more recent incarnation (Joanisse & Seidenberg, 1999), the critical feature of this approach is the manner in which different types of verbs depend on contributions of the phonological and semantic components of the language system. In a previous paper (Patterson et al., 2001), we made a case for the twin claims: (a) that the patients whose performance is characterized by a striking pattern of regular > irregular have semantic impairments and (b) that irregular forms, in any language transcoding operation, depend more than regular forms do on a contribution from word meaning (see also Plaut, McClelland, Seidenberg, & Patterson, 1996). The current paper is concerned with the other side of the dissociation, and its goal is to make a case for the twin claims: (a) that the patients whose performance is characterized by a pattern of irregular > regular have phonological impairments and (b) that, relative to most irregular past-tense forms, regular past-tense English verbs place greater demands on the phonological system, because the transformation from regular stem to past always involves the addition of extra phonemes whereas this is rarely the case for irregular verbs.

Regular English verbs make up approximately 86% (by type count) of verb vocabulary (Plunkett & Nakisa, 1997). The stem is transformed into the past tense by the addition of *-ed*, with the resulting phonological form dependent on the final phoneme of the stem. The final alveolar stop in the regular past tense is consistent with the voicing of the preceding phoneme. Thus stems ending with a voiced phoneme (*stab*, *love*, *raise*) add the voiced allophone [d] in the past tense; those ending with unvoiced phonemes (*stop*, *laugh*, *race*) add the unvoiced version [t]; and those already ending with either the voiced or unvoiced alveolar stop (*fade*, *hate*) acquire an extra syllable [ɪd].

The remaining 14% of verbs form their past tenses in a variety of irregular ways, including no change (*hit, spread*); change from final [d] to [t] (*lend* → *lent*, *send* → *sent*); simple vowel change (*win* → *won*, *choose* → *chose*); complex transformations involving vowel change plus change to or addition of final alveolar (*think* → *thought*, *say* → *said*, *keep* → *kept*); and a few very high frequency suppletives (*go* → *went*, *am* → *was*). Note that there are several factors that keep 'irregular' in this context from being completely unpredictable. One is the existence of many form-related families such as *ring* → *rang*, *sing* → *sang*; *weep* → *wept*, *creep* → *crept*; *bend* → *bent*, *send* → *sent*; and so on. Another is that about 60% of irregular past-tense forms, like all regular past tense forms, end with an alveolar stop (see McClelland & Patterson, 2002a, for a discussion of the considerable systematicity in 'irregular' past-tense formation).

The characteristics and predictions of various versions of both single- and dual-mechanism accounts of past-tense processing have been described in a number of recent papers (e.g., McClelland & Patterson, 2002b; Pinker & Ullman, 2002; Tyler et al., 2002a). It therefore seems unnecessary to rehearse these views in detail here. Instead we will focus on a specific phonological difference between regular and irregular past-tense forms—i.e., the fact that regular verbs always, but irregular verbs only rarely, add extra phonemes to become past tense—plus a neurolinguistic account of why this might be a vital factor for the main group of aphasic patients who have been reported to demonstrate particular difficulty with the regular past tense. These patients, called 'anterior aphasics' by Ullman et al. (1997) and 'nonfluent aphasics' by Ullman et al. (in press), have lesions centered on anterior portions of the left hemisphere. Their language disorder fits in the spectrum of Broca's aphasia, which is a deficit of both phonetic/phonemic and grammatical aspects of language processing. Perhaps the most striking and consistent symptom of Broca's aphasia is difficulty in articulation, which results in "... striving toward a phonologically simpler form" (Brown, 1972, p. 112).

The implication of this phonological deficit is that, in assessing such patients' ability to produce X versus Y (whether X and Y correspond to past-tense regular and irregular verbs or to any other speech-production contrast apart from phonology itself), it is crucial to equate

X and Y as closely as possible for phonological complexity. Furthermore, although the original characterization by Broca emphasized the expressive speech difficulties, particularly articulatory deficits, of such patients, their receptive speech processing is also compromised (Caplan, 1987). Once again, then, if such patients performed poorly in receptive processing of word type X (e.g., past-tense regular verbs) relative to Y, one would need to ask whether X and Y were matched on phonological factors before attributing the effect to some other domain of language competence. Although we are applying this notion in a specifically neurolinguistic context, it is in fact an instance of the more general principle stated succinctly by Stemberger (1995): "If we wish to interpret some outcome as evidence about morphology, possibly as part of an argument that there are morphological rules, we must be sure that the outcome is not a by-product of general morphology-independent processing in some other language component" (p. 248). In this and other of his writings (e.g., Stemberger, 2002; Stemberger & Middleton, in press), Stemberger emphasizes that observed differences in performance between regular and irregular forms may be the result of phonological rather than morphological factors.

We do not mean to imply that all aspects of Broca's aphasia are attributable to a phonological deficit. The patients' well-documented difficulties in processing grammatically complex sentences, for example, may reflect deficits in the representation of syntactic and/or morphological information which could disrupt past-tense processing. Our point is that such consequences would affect irregular as well as regular verbs. The aim of the present investigation is to inquire whether, once important phonological factors have been controlled, the patients have any differential difficulty with the regular past tense.

In the sentence completion or elicitation task that has become standard for assessing past-tense production, Ullman et al. (1997) reported a significant advantage for irregular verbs relative to both regular real and nonce verbs in one patient with Broca's aphasia (case FCL). An advantage for irregular > nonce verbs in this task was also significant in a group of patients with Parkinson's disease (PD), who should have 'functional' lesions in frontal cortex due to reduced input from the basal ganglia. In the main list of items for which these results obtained, the irregular, regular and nonce verbs were not matched on phonological characteristics. Ullman et al. were, however, concerned to rule out the possibility that articulatory difficulties might have contributed to their findings for cases of PD, and therefore retested four of the most hypokinetic PD cases on sentence completion using a new list of past-tense irregular and regular verbs ($N = 21$ each, called the PD Retest) matched for final consonant structure (e.g., *heard/stirred*). This test yielded a reliable advantage for irregular over regular verbs (87 and 70% correct, respectively). Nevertheless, we suggest that these results do not resolve the issue of a contribution from phonological deficits to an apparent morphological effect, for several reasons.

First, the regular and irregular items in the PD Retest were matched on final, but not initial, consonants, and the regular verbs on average had more pre-vocalic consonants. For example, the list contained 'matched' pairs like *heard/stirred*, *made/played* and *ate/stayed*; in all of these examples, the regular but not the irregular verb begins with a consonant cluster. Although the fairly systematic difference between regular and irregular verbs is in the addition of terminal phonemes (which occurs always in regular, but only occasionally in irregular, verbs when the stem is transformed to past tense), extra phonemes at any position in the word can be expected to cause difficulty for patients with an articulatory deficit.

Second and of greater relevance here, the Broca's aphasic patient FCL—the only patient of any type in Ullman et al. (1997 or in press) reported to show a significant irregular > regular advantage in the task of sentence completion on the authors' main list of items—was not assessed on the PD Retest. A number of other nonfluent aphasics (Ullman et al., 1997 and Ullman et al., in press) demonstrated a significant pattern of irregular > regular in reading past-tense verbs on a list where the items ($N = 17$ each regular and irregular) were matched for terminal consonant structure. The task of reading aloud, however, as we shall argue in the experiments below, is subject to other influences that may vary between regular and irregular past-tense forms. There are, at present, no published data demonstrating a significant irregular > regular pattern in elicitation of past-tense forms where the materials are well matched for phonological structure.

The main focus of the current investigation is this: If, as concluded by Ullman et al. (1997) and Ullman et al. (in press), there is a reliable pattern of irregular > regular past-tense production in Broca's aphasia that results from disruption of a procedural rule system, it should be maintained on phonologically controlled materials. If, on the other hand, the observed disadvantage for regular past tense verbs derives from their phonological complexity, it should be eliminated by phonological matching of items.

Because phonological complexity constitutes the essence of both our experimental manipulations and our conceptual account of the results, it is essential to be explicit about the operational definition of this term employed here with respect to past-tense verb forms. When we say that the regular past-tense in English is, on balance, more complex than the irregular, we are specifically and only contrasting the phonological characteristics of words like *blinked* (the past tense of the regular verb *blink*) with the phonological characteristics of words like *thought* (the past tense of the irregular verb *think*). That is, our definition of complexity does not refer to the nature of the transformation from the stem to the past tense but only to the spoken past-tense forms themselves. Our claim is that *blinked* is complex because its phoneme sequence, /blɪŋkt/ is CCVCCC, whereas *thought*, consisting merely of a CVC sequence, is much simpler to hear and to say.

Outline of the investigation

The first inclusion criterion for participants in the current investigation specified nonfluent aphasic patients who showed a numerical (not necessarily statistically reliable) advantage for irregular > regular past-tense verb production in at least two of the three production tasks included in our study (sentence completion, reading, repetition), with at least equivalent performance on the third, i.e., no reversals to regular > irregular. The second criterion was that the patient be willing to undertake extensive testing. We screened 50 individuals who were clinically described as nonfluent aphasics following a left-lateralized cerebrovascular accident (stroke). Ten of these 50 cases fulfilled the two inclusion criteria and hence constituted the participants for this study. Although the patterns of performance in the remaining 40 screened patients are of interest, they are not directly germane to the hypothesis under consideration and will not be included in this paper.

The screening test for the 10 participants formed Experiment 1. Experiment 2 comprised more extensive testing of these 10 nonfluent aphasic patients on the same three production tasks (sentence completion, reading, repetition) where the materials included target sets of regular and irregular past-tense forms matched on our operational definition of phonological complexity, CV structure. Experiment 3 extended our hypothesis regarding the central role of a phonological deficit in the language performance of the nonfluent aphasic patients, by examining their success on a receptive task involving spoken regular verb stems and their past-tense forms (e.g., *bowl/bowled*) together with word pairs that have a similar phonological structure but no morphological relationship (e.g., *coal/cold*). Experiment 4 applied the materials from Experiment 2 in the sentence completion task to a small group of patients ($N = 5$) with semantic dementia; the purpose of this experiment was simply to establish that the dramatic regular > irregular advantage obtained in our previous study of semantically impaired patients (Patterson et al., 2001) would be replicated with this new set of materials.

Nonfluent aphasic participants and background assessments

Patient details and aetiology for $N = 10$ nonfluent aphasic cases are shown in Table 1. The patients completed a battery of assessments to give a profile of general language and semantic capabilities, and these results are shown in Table 2. Digit span was assessed in the usual manner, with digits presented at 1/s for immediate repetition. The individual patients' results are displayed here and throughout the remainder of the paper in ascending order of digit span. Spontaneous speech fluency was assessed by calculating the number of words produced per minute during a description of the Cookie Theft picture from the Boston Diagnostic Aphasia Examination (Goodglass & Kaplan, 1983). By this measure, all patients were substantially dysfluent relative to normal controls: in a study by Bird, Lambon Ralph, Patterson, and Hodges (2000), with normal participants of similar age and background to the patients in the current study, the slowest normal adult spoke at 96 wpm

Table 1
Patient details

Patient	Age	Sex	Aetiology/CT report
BB	60	F	1996 L CVA during operation for R acoustic neuroma
IJ	61	M	1995 low attenuation L frontal, temporal and parietal lobes, MCA ischaemic infarct
IB	53	F	1990 subarachnoid haemorrhage from L MCA aneurysm and infarct
DE	64	M	1997 non-haemorrhagic infarct L MCA territory
AB	61	F	1996 embolic CVA L MCA territory
MB	83	F	1998 non-haemorrhagic L frontoparietal infarct (5 months previously 2 small R frontal infarcts)
RT	58	M	1987 L CVA
VC	65	F	1998 low attenuation L frontal and parietal lobes, ischaemic infarct
GN	72	M	1999 L frontal infarct in MCA territory, also established low density lesion in L occipital lobe
JL	46	F	1996 L CVA involving temporal, parietal and frontal lobe

Table 2
General language assessments

Patient	Digit span	Spontaneous speech: words per minute	TROG/20	Reading/80 (HI /40 LI/40)	Naming/64	Word-picture matching/64	PPT/52
BB	1	36	10	14 (HI 12, LI 2)	7	64	48
IJ	2	9	5	15 (HI 13, LI 2)	21	63	49
IB	2	22	9	32 (HI 27, LI 5)	33	62	49
DE	3	10	6	33 (HI 20, LI 13)	34	64	50
AB	3	5	8	32 (HI 29, LI 3)	42	62	47
MB	3	27	10	28 (HI 17, LI 11)	35	60	47
RT	3	39	15	76 (HI 32, LI 24)	33	63	43
VC	4	18	7	59 (HI 32, LI 27)	42	56	43
GN	4	27	10	40 (HI 29, LI 11)	48	60	45
JL	5	47	19	72 (HI 39, LI 33)	54	64	51

Table 3
Phonological assessments

Patient	Rhyme judgment/48	Rhyme production/24	Segmentation/96
BB	14	0	Unable
IJ	23	10	3
IB	22	0	Unable
DE	18	2	Unable
AB	22	7	Unable
MB	16	0	Unable
RT	48	7	22
VC	23	4	14
GN	21	8	34
JL	48	16	61

when describing this same picture. All patients were impaired at receptive syntax as measured by the number of blocks passed (maximum = 20) in the Test for the Reception of Grammar (TROG; Bishop, 1989). There was considerable variability in reading and object naming success, but all 10 patients were impaired on both. In PALPA test 31 (Kay, Lesser, & Coltheart, 1992), which assesses single word reading aloud with manipulations of word frequency and imageability, all patients were more successful at reading the higher imageability items, and this difference was significant for the patients as a group and for BB, IJ, IB, AB, and GN as individuals. Picture naming and spoken word-to-picture matching were assessed with the same 64 item target set (Bozeat, Lambon Ralph, Patterson, Garrard, & Hodges, 2000). Picture arrays for the word-to-picture matching test consisted of the target plus nine distractors from the same semantic category. As shown in Table 2, all patients performed reasonably well on word-to-picture matching and also on the three-picture version of the Pyramids and Palm Trees Test (PPT; Howard & Patterson, 1992), a test that assesses knowledge of semantic associations amongst object concepts. As the lowest control scores on these last two tests in the Bozeat et al. (2000) study (again with normal participants appropriate as controls for the current patient sample) were 62/64 and 49/52, respectively, a few of the current sample of patients were mildly below the normal range on semantic testing; but none had a major deficit in semantic knowledge, at least for concrete concepts.

Table 3 shows the results of three metalinguistic phonological assessments (from Patterson & Marcel, 1992): rhyme judgment, rhyme production, and phonemic segmentation (addition and subtraction of initial phonemes). While there was considerable variation in performance within the group, these results establish that all the patients were impaired in these kinds of explicit phonological tasks on which control subjects perform at ceiling. Half of the patients were unable even to make an attempt at adding and subtracting the initial phonemes of words.

Experiment 1: Verb screening assessments

Methods

Participants

The participants for this experiment were the 10 nonfluent aphasic patients described above.

Materials

Two sets of materials comprised the screening test. The first set contained 24 regular and 24 irregular verbs (listed in Appendix A) matched for frequency and imageability; these were administered across the three tasks of sentence completion, repetition and reading aloud. The second set consisted of lists previously used by Ullman et al. (1997, in press), including: (a) the 40 verbs (half regular, half irregular) that formed Ullman et al.'s main past tense production task, which we administered in both sentence completion and repetition; and (b) the 34 verbs (their so-called 'anterior aphasic reading list', again half regular and half irregular) which we used to test reading only.

Procedure

Because patients of this type find the sentence completion task difficult and may fail to provide any response at all, we attempted to maximise the patients' chances of responding by giving them simultaneous written and spoken presentation of the sentences. In all other regards, the paradigm was the standard cloze technique, in which a first sentence using a particular verb in its stem form appropriate for the present tense was followed by a sentence demanding the past tense with the verb omitted (e.g.,'Today I dig a hole. Yesterday I ____ a hole'). Subjects were asked only to produce the missing word, and were told that it should be the same verb but in its past-tense form. The same items were presented singly for immediate repetition (i.e., no delay was inserted between presentation and response) and reading aloud (in response to lower-case printed words) of both stem and past-tense forms. Subsets of the stimulus lists were organised such that patients never encountered the same stimulus item more than once within a given testing session.

During testing, the experimenter transcribed each response as accurately as possible, but all of the sessions were also audio-taped for later confirmation and/or correction of the responses transcribed at the time of testing. In cases where a patient produced more than one attempt at a response, the first response was the one to be scored. Scoring was strict in that only completely accurate responses were accepted as correct. These details of testing and scoring apply to all of the production experiments included in this study.

Results

The proportions of correct responses to the full set of items in the screening tests ($N = 88$ items for sentence completion and repetition, $N = 82$ for reading) are displayed for each patient in each task in Fig. 1. As a group, the patients exhibited a highly significant advantage for producing irregular compared to regular past-tense forms in all tasks. The mean proportions of

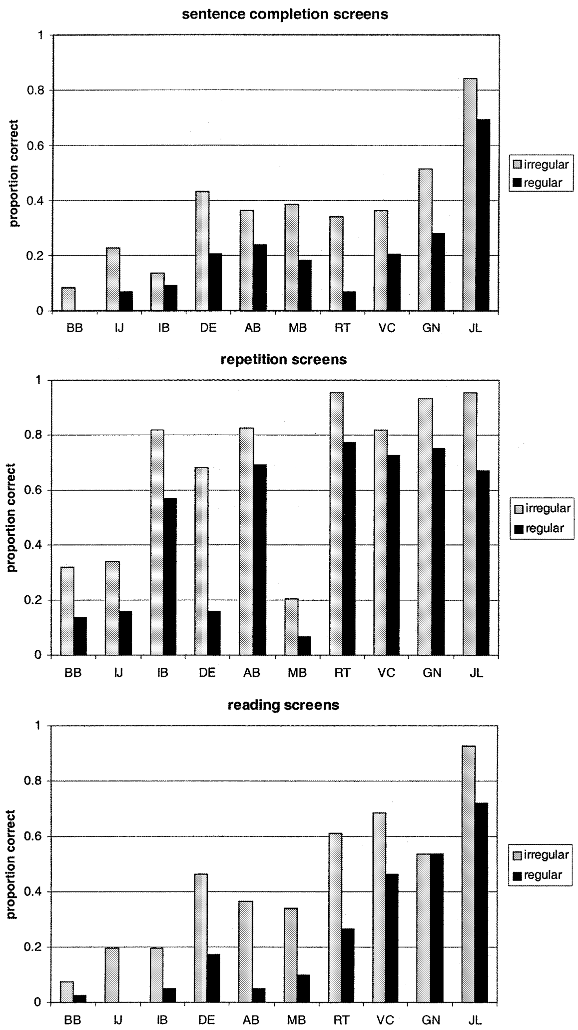

Fig. 1. Past-tense production on the screening tests: Proportion of correct responses by each patient to regular and irregular verbs in sentence completion, repetition, and reading of the screening materials.

correct responses for irregular and regular verbs, respectively, were .37 and .20 in sentence completion ($t(9) = 6.24$, $p < .001$), .68 and .47 in repetition ($t(9) = 5.51$, $p < .001$), and .44 versus .24 in reading ($t(9) = 5.61$, $p < .001$).

For individual patients (all χ^2 results reported are two-tailed unless otherwise stated), the irregular > regular advantage in sentence completion was significant for DE ($\chi^2 = 4.24$, $p = .039$), RT ($\chi^2 = 8.45$, $p = .004$) and GN ($\chi^2 = 5.60$, $p = .018$); using a 1-tailed test, this difference was also reliable for IJ and MB. In repetition, significant effects were found for IB ($\chi^2 = 534$, $p = .021$), DE ($\chi^2 = 22.57$, $p < .001$), RT ($\chi^2 = 4.73$, $p = .030$), GN ($\chi^2 = 4.16$, $p = .041$) and JL ($\chi^2 = 11.00$, $p = .001$), with 1-tailed significance for BB and IJ. In reading, the advantage for irregular past tenses reached significance for IJ (Fisher's Exact $z = 2.59$, $p = .010$), DE ($\chi^2 = 6.61$, $p < .001$), AB ($\chi^2 = 10.69$, $p = .001$), RT ($\chi^2 = 8.37$, $p = .004$) and JL ($\chi^2 = 4.71$, $p = .030$) with additional 1-tailed significance for IB and VC.

Summary

We have established that the individuals in this group were markedly impaired in producing the past tense forms of all verbs but significantly more so for regular verbs, and also that they all had a phonological impairment. The question to be addressed is whether the phonological impairment might be entirely or largely responsible for the significant difference between regular and irregular items in past tense production, and whether controlling for phonological complexity would therefore essentially eliminate the discrepancy. We also wanted to examine other factors affecting performance in the production tasks, as these might also have a bearing on differential success with regular and irregular verbs. We have already shown, for example, that imageability is a crucial predictor of reading performance for all the patients in this group.

Experiment 2: Main verb production experiment

Methods

Participants

The participants for this experiment were the 10 nonfluent aphasic patients described above.

Materials

In order to facilitate the examination of psycholinguistic variables, we chose a large set of 126 irregular single syllable verbs. All had exclusively irregular past tense forms; that is, as recommended by Ullman (1999), we excluded verbs that can be optionally treated as regular, such as *dive* → *dove* or *dived*. A further 126 regular single syllable verbs were selected; and this 252-item set included a subset of 34 regular and 34 irregular verbs matched pairwise for CV structure of the past-tense forms, rated imageability of the stem forms (Bird, Franklin, & Howard, 2001; Coltheart, 1981), and frequency. Two frequency measures were used for matching, both from Celex (Baayen, Piepenbrock, & Gulikers, 1995) and both combined for spoken and written samples: the log of the lemma frequency count for each verb, and the log of the specific frequency of the past-tense form of each verb. This set of 68 items is shown in Appendix B. Also included in the fuller list was a subset of 84 regular verbs (listed in Appendix C) for which the past tense forms comprised 28 of each of the three allophones [d], [t] and [ɪd], controlled for frequency, imageability and CV structure of the stem (those stems with a final alveolar stop necessarily became two-syllable words in the past tense). The motivation for this manipulation was to compare [d] / [t] versus [ɪd], to determine whether the increase in number of syllables from one to two associated with [ɪd], along with the accompanying reduction of final consonant cluster size, would affect performance.

In addition to the 252 real verbs, a pseudo-word was created for each verb that differed from its real-word mate typically by only one and at most by two phonemes. The sentence completion task with pseudo-words employed the same cloze paradigm as described above. The sentences used for real verbs and pseudo-words were identical, but the phonologically similar pseudo-word for each real verb was embedded in a sentence created for a verb other than its mate. This was to avoid having the pseudo-words sound like real verbs that might plausibly fit into the sentence.

Procedure

With 252 real verbs and an equal number of pseudo-verbs, the sentence completion task consisted of 504 sentences. These 504 were semi-randomized and divided into eight blocks of 63 items each with roughly equal numbers of each stimulus type (regular real, irregular real, and pseudo-word) per block; typically only 1–2 blocks of sentence-completion items were administered in a given testing session. This is an extremely difficult task for patients of this type. Due to very slow rates of responding and intolerance to this form of assessment, AB, BB and IJ completed only the controlled subset of 34 each of regular and irregular real verbs in sentence completion; and unfortunately VC was not available to take part in any sentence tasks following the screening assessment. The remaining six patients completed the full set of 252 real and 252 pseudo-verb stimuli in the sentence completion paradigm. For the repetition and reading assessments, the same set of items was used, but in addition we asked the patients to repeat and read the uninflected stem forms of all items. Thus the total number of stimuli in each of these tests was 1008; these were again divided for presentation into eight blocks, here of 126 items each. Administration of the blocks was arranged such that patients never encountered the same stimulus item more than once within a testing session. All 10 patients completed the repetition and reading assessments. The tasks were administered in the same manner as in the screening assessments: sentence completion incorporated simultaneous spoken and written presentation of the sentences; in repetition, the word was spoken to the patient who was allowed to respond immediately; and in reading aloud, the words printed on cards were displayed one at a time for an oral reading response.

A complete analysis of performance, assessed both by accuracy rates and the nature of the errors, for all patients on all items and in all tasks would entail very lengthy description. Because the specific hypotheses expressed in the Introduction are addressed primarily by results concerning real-word past-tense forms rather than nonce verbs, we restrict ourselves to presenting the word data here, with special emphasis on the subsets of items matched for phonological structure. We also present only a minimal description of error types. More detailed results for the full sets of words and pseudowords, plus distributions of error types in all tasks, will appear in a separate paper.

Results

Matched subset: Accuracy

Fig. 2 displays the individual patients' performance in all three production tasks on the subset of 34 regular and 34 irregular verbs controlled pair-wise for CV structure as well as imageability and word frequency; and Table 4 provides the proportion correct for each item in this matched subset for each task, plus means across items. The irregular > regular advantage that we had observed for the same patient group in the screening assessments in both sentence completion and repetition (see Fig. 1) was no longer significant for these two tasks when performed with the complexity-controlled materials. The mean proportions of correct responses to irregular and regular verbs in sentence completion (for $N = 9$ patients) were .26 and .29 (hence, a slight numerical advantage for *regular* past tense forms, though obviously not significant); in repetition (for $N = 10$ patients), mean success rates were .65 (irregular) versus .64 (regular). No individual patient demonstrated a significant difference between regular and irregular verbs in either task. The absence of any selective difficulty with regular verbs on the complexity-controlled materials supports the hypothesis that the previously seen disadvantage in sentence completion and repetition was due to the greater phonological complexity of regular past tense forms. In the reading task, however, the CV-controlled items still yielded a significant advantage for irregular forms across the group (.41 versus .27, $t(9) = 4.56$, $p = .001$). This effect reached significance at an individual level for two cases, DE ($\chi^2 = 6.01, p < .05$) and RT ($\chi^2 = 5.22$, $p < .05$).

The residual advantage for the irregular past tense in reading may be due at least in part to the visual representations and/or alternative meanings of these items, in at least three different ways. First of all, it is well established that Broca patients have particular difficulties reading abstract words, as shown in this patient group by their differential success in reading high- versus low-imageability words (Table 2). It is therefore germane to note that some irregular past tense forms are homographs of other, more concrete words: in our set, these include *lent* (which is a familiar proper noun in Britain, although usually spelled with a capital L), *cast, left, ground, stole, spoke, wound* and *bit*. In a regression analysis with regularity and homograph status included, although the latter variable does not quite reach significance [$t = 1.60$, $p = .12$], its presence reduces the regularity effect in the patients' reading performance from highly reliable to borderline significance [$t = 1.88$, $p = .07$]. A second relevant factor is that the past tense forms of some irregular verbs are identical to their stems (e.g., *let*, *split* and *cast*). On verbs other than these, all of the patients were much more successful at reading uninflected stem forms compared to the past tense of the same irregular verbs; it is therefore reasonable to assume that some or all 'no change' verbs were read as if they were stem forms. In support of this proposal, *read*—

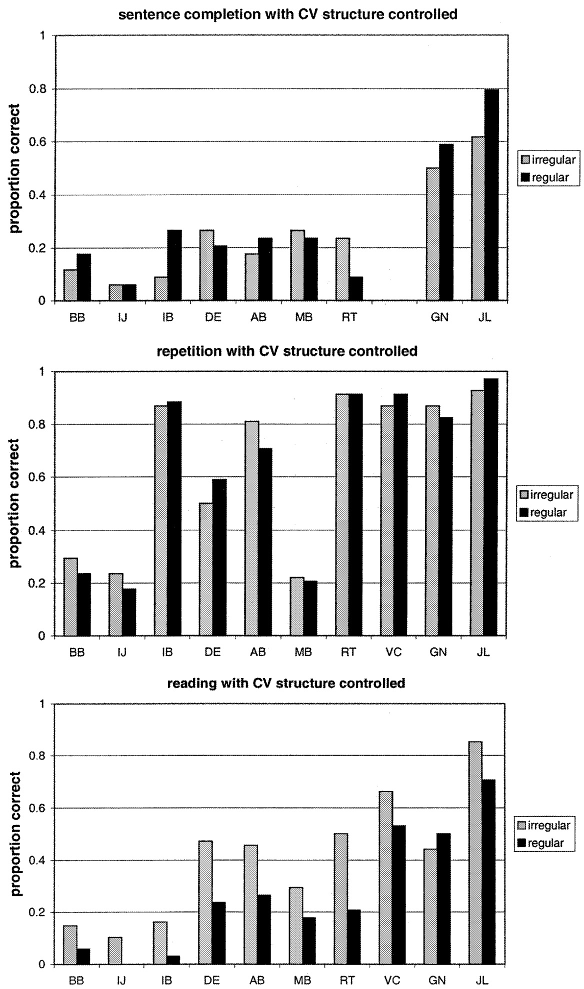

Fig. 2. Past-tense production on the critical subset of items: Proportion of correct responses by each patient to regular and irregular verbs in sentence completion, repetition and reading of the sets of regular and irregular verbs matched for past-tense CV structure.

Table 4
Mean proportion correct for producing each past-tense verb in the matched subset of regular and irregular verbs for each task. Proportions are out of $N = 9$ patients for sentence completion and $N = 10$ for repetition and reading

Regular verbs				Irregular verbs			
Item	Sentence	Repetition	Reading	Item	Sentence	Repetition	Reading
seemed	0.11	0.6	0.2	meant	0.11	0.6	0.5
lived	0.33	0.6	0.3	kept	0.22	0.5	0.2
named	0.11	0.5	0	lent	0.22	0.7	0.7
tried	0.44	0.6	0.4	brought	0.11	0.5	0.2
guessed	0.33	0.4	0.2	cast	0.44	0.4	0.35
used	0.44	0.6	0.2	left	0	0.6	0.3
laid	0.44	0.8	0.4	won	0.33	0.9	0.6
showed	0.33	0.9	0.1	let	0.67	0.65	0.5
trained	0.11	0.5	0.2	ground	0.44	0.5	0.5
towed	0.22	0.8	0	bade	0	0.8	0.2
gained	0.11	0.5	0.1	bent	0.11	0.6	0.5
failed	0.33	0.5	0.2	sold	0.11	0.6	0.9
died	0.33	0.8	0.4	bought	0.67	0.8	0.6
pulled	0.33	0.5	0.3	built	0.22	0.8	0.6
filled	0.33	0.9	0.2	dealt	0.22	0.8	0.1
flowed	0.11	0.6	0.2	slid	0.22	0.6	0
viewed	0.22	0.3	0.1	fled	0	0.8	0.2
weighed	0.56	0.8	0.3	rode	0.44	0.7	0.5
called	0.22	0.8	0.2	held	0.11	0.8	0.6
sighed	0.33	0.9	0.3	shook	0.56	0.7	0.3
chewed	0.44	0.7	0.6	dug	0.22	0.6	0.5
sewed	0.33	0.8	0.2	rang	0.22	0.7	0.5
stewed	0.22	0.4	0.2	split	0.22	0.45	0.25
played	0.22	0.7	0.2	swung	0.22	0.5	0.2
sprayed	0.11	0.7	0.1	strode	0.22	0.4	0.2
paid	0.22	0.7	0.6	taught	0.33	0.7	0.6
dropped	0.33	0.5	0.6	slept	0.22	0.6	0.2
prayed	0.11	0.7	0.2	stole	0.44	0.3	0.5
cried	0.44	0.7	0.6	spoke	0.22	0.7	0.4
slapped	0.22	0.6	0.4	swept	0.33	0.6	0.2
wiped	0.22	0.7	0.3	wept	0.33	0.6	0.5
howled	0.44	0.7	0.3	wound	0.22	0.6	0.3
tied	0.44	0.8	0.2	bit	0.22	0.8	0.6
fried	0.44	0.6	0.4	froze	0.11	0.8	0.5
Mean	0.29	0.65	0.27	Mean	0.26	0.64	0.41

Note: The apparent oddity of four values in the irregular section of Table 4 (two for reading, two for repetition) that are not multiples of .10 is attributable to the fact that *cast let* and *split* are all verbs with identical forms in stem and past tense. Because these verbs were presented twice and there was no way for the patient to know which presentation was intended to be a stem and which a past-tense form, if a patient repeated or read the word correctly on one presentation but incorrectly on the other, he or she was given a score of 0.5 for the past-tense condition.

which is a homograph but not a homophone in stem and past forms—was always pronounced /rid/ corresponding to the present tense or stem. Finally, patients of this type very often produce a reading response consisting of a different real word that is orthographically similar to the target word. The regular*—ed* suffix may be at particular risk of yielding such visual errors in reading, for two different reasons. The first is that deletion of this suffix, resulting in the stem form, will inevitably constitute an orthographically similar word. Secondly, replacing *-ed* with *-er*, as well as typically creating a more imageable word, also yields a very visually similar item. Many of the reading errors to regular past-tense forms in our study did indeed consist of responses like *flowed* → "*flower*" and *prayed* → "*prayer*".

Matched subset: Errors

Table 5 presents a breakdown of the patients' errors in the three past-tense production tasks into five major types of error. *Stem* indicates that the patient produced the stem or uninflected form of the verb when he or she was meant to be generating (in sentence context) or

Table 5
Proportions of the five major error types to the matched subset of verbs (34 regular [REG] and 34 irregular [IRREG]) in the three past-tense verb production tasks

	Sentence		Repetition		Reading	
	REG	IRREG	REG	IRREG	REG	IRREG
Stem	0.36	0.38	0.20	0.02	0.18	0.08
Morphological	0.09	0.11	0.06	0.02	0.08	0.04
Phonological	0.02	0.02	0.19	0.46	0.12	0.24
Omission	0.00	0.02	0.00	0.00	0.07	0.06
Other	0.53	0.48	0.55	0.50	0.55	0.58

repeating or reading the past-tense form. *Morphological* indicates that the patient produced a different inflected form of the target verb; almost all of these were *-ing,* a form that is very common in the speech of patients with Broca's aphasia, though a few patients occasionally produced *-s* responses as well. *Phonological* means an error response that had clear and substantial phonological overlap with the target, with the criterion that $\geqslant 50\%$ of the phonemes in the response must be shared with the target word. Some of these were different words (e.g., *trained* → "tame") but many were nonwords indicative of phonological problems in speech production (e.g., *trained* → "tane"). *Omissions* are self-explanatory. *Other* refers to responses with so little resemblance to the target that one does not know how to classify them (e.g., *trained* → "neck").

Stem errors were far more common in the sentence completion task than in the other two production tasks; this is scarcely surprising given that the patients had just heard and seen the stem form of the verb in the first sentence of each pair in the completion task, whereas the only stimulus presented in both repetition and reading was the past-tense form of the verb. Nevertheless, stem forms were produced in these two tasks, and more often to regular verbs; again this is not surprising since the phonological or orthographic past-tense form of a regular verb contains the stem. Close phonological errors only occurred with any frequency in repetition and reading, and more often to irregular than regular verbs. The size of the verb-type discrepancy in stem errors (REG > IRREG) for repetition and reading is similar to the size of the reverse discrepancy in close phonological errors (IRREG > REG). This may suggest that stem errors arise as much if not more from a phonological than a morphological deficit. Phonological simplification of, or distortion to, a past-tense regular form like *danced* has some likelihood of resulting in the stem form *dance*, whereas the same sort of phonological error process operating on an irregular past form like *rang* is more likely to produce a response like *ran* or *rank.*

The fact that both stem and morphological (mostly *-ing*) errors in the sentence completion task were just as common to irregular as regular verbs merits some comment. These errors to both verb types may be attributable to phonological impairment in a broader sense than the specific issue of phonological complexity of regular and irregular past-tense forms. For example, the relationship between phonological processing and working memory is well established, and nonfluent aphasic patients always have reduced capacity in verbal working memory (Caplan, 1987). The sentence-completion task makes substantial demands on working memory that do not apply to single-word reading or repetition. Under such demands, if the task becomes too hard, the patients may sometimes resort (though probably not consciously) to reproducing the stem form that they have just seen and heard in the first sentence of the pair, or to producing the*—ing* form that is so characteristic of their spontaneous speech. Both of these tendencies could apply equally to regular and irregular verbs. Another possibility is that these errors reflect some disruption to the underlying knowledge that the gap in the sentence completion task requires a past-tense form: as previously discussed, patients with Broca's aphasia do exhibit deficits in morpho-syntactic competence as well as in phonological processing. Whether non-phonological types of knowledge contributed to this outcome, and whether these involve morphology, other types of grammatical competence, or abstract semantic information necessary to specify tense, cannot be determined without additional research. It should be emphasized, however, that whatever factor or combination of factors is responsible, it appears to apply equally to regular and irregular forms. This pattern is consistent with a single integrated system account, and fails to provide any specific support for the dual-mechanism theory.

As correctly pointed out by Ullman et al. (in press), the phonological deficit account of past-tense processing in Broca's aphasia predicts that, just as final stops are often omitted from the past tense of regular verbs by these patients, they should also be omitted from phonologically similar irregular past tense forms. The nonfluent patients in their study, however, never produced responses such as "kep" as the past tense form of *keep.* Some of the patients did omit final alveolar stops when reading stem forms of irregular verbs (e.g., *send* → "sen"). One could argue that such omission errors to irregular targets might occur less often than to regular past tense forms, due to the resulting production of a non-word. It cannot be denied, however, that the phonological errors made by nonfluent patients do frequently result in non-words. On the irregular verbs in our phonologically controlled subset ($N = 34$), the patients in this study made very few errors that consisted solely of the omission of a final alveolar stop; but there were some. DE gave "hel" in response to *held* in reading and repetition; both DE and IJ produced "sole" as the past tense of *sell* in sentence completion. These omissions do, however, result in real words; similar errors yielding nonword responses numbered only 13 in total.

One dramatic message from this basic error analysis is the very high proportions of *other* errors, to both verb types and in all tasks (though unsurprisingly somewhat lower in repetition where the patient was given a phonological model of what to say). The very restricted language competence of patients with Broca's aphasia is severely taxed by past-tense verb production tasks, and they are often unable to say anything that identifiably resembles the target word, whether it is a regular or an irregular past-tense form.

Matched subset: Further analyses

In creating subsets of regular and irregular verbs so closely matched on phonological characteristics, might we have biased the materials in some other way that would eliminate or reduce the previously observed regularity effect in past-tense production? Although the purest version of a dual-mechanism account assumes a complete dichotomy between regular and irregular items and the mechanisms by which they are processed, many dual-route theorists acknowledge that the picture is a little less clear-cut, in at least two ways that might be pertinent here. First is the possibility of a productive, rule-governed component (Halle & Marantz, 1993; Halle & Mohanon, 1985), rather than a purely associative mechanism, for processing of irregular verbs: this would apply especially to items in which the transformation to past tense includes the addition of a terminal alveolar stop (e.g., *mean* → *meant*, *leave* → *left*, *sell* → *sold*). Because the past tense forms of all regular verbs end in an alveolar stop, our effort to match regular and irregular verbs for CVC structure resulted in the inclusion of a number of irregular verbs with this kind of d/t 'affix'. To the extent that some rule-like concatenation applies overtly to these, they might be more difficult than pure vowel change irregulars like *win* → *won*, *ride* → *rode* or *freeze* → *froze*.

To assess this possibility, we compared the patients' performance on each task between the $N = 15$ irregular verbs in our matched subset that involve only a vowel change and therefore a null affix, and the $N = 10$ irregular verbs with clear d/t affixes. The prediction from the dual-mechanism account to be tested is that performance should be significantly better on the former than the latter. Note that this analysis includes only 25 of the 34 irregular verbs in our target set, because we excluded from the analysis: (a) the three no-change irregular verbs ending in [d] or [t] (*bid, split* and *cast*); (b) the three irregular verbs (*lend, bend, build*) that already end in an alveolar stop in the stem form and merely change this from [d] to [t] for the past tense; and (c) the two items (*bring* → *brought* and *teach* → *taught*) that acquire a final [t] in past-tense form but, rather than being an addition, the [t] replaces a very different terminal consonant in the stem form, and the transformation also involves a major vowel change; both of these factors make it seem implausible that this would engage a form of affixation or concatenation.

In sentence completion, the proportions correct for vowel change vs d/t affixed irregular items were .28 vs .22: by subjects, $t(8) = 0.91$, $p = .37$; by items, $t(23) = 0.94$, $p = .37$. Although these *t*- and *p*-values are a long way from significance, the difference was in the predicted direction. We therefore computed a further regression analysis on the by-items data including word length as a variable (number of phonemes in the past-tense form) because the 'affixed' items were slightly longer (mean = 4.1 phonemes) than the vowel-change verbs (mean = 3.7 phonemes). With length thus included, the impact of 'affix' status moves even farther from significance, $t(23) = 0.58$, $p = .57$.

In repetition, proportions correct were .64 for vowel change vs .65 for d/t 'affixed', obviously not different. And for reading, the result was reversed, though not reliably, from the predicted direction: .23 correct for vowel change vs .29 for pseudo-affixed: by subjects, $t(9) = 0.15$, $p = .88$; by items, $t(23) = 0.18$, $p = .86$.

A second issue that requires consideration and additional analysis concerns Ullman's (1999, 2001) proposal that 'inconsistent regular verbs'—i.e., those which rhyme with one or more irregular verbs (e.g., *glide*, which is regular but resembles *ride* and *hide*, both of which are irregular; or the regular *blink*, which resembles the irregulars *think* and *drink*)—might engender lexical listing of their past-tense forms. A stored regular past form would ward off the possibility of the speaker producing an inappropriate irregular past for a regular item (like "glide" → "glode") by analogy with the rhyming neighbour. By this hypothesis, patients with a procedural rule deficit might be expected to perform relatively well on inconsistent regulars; and, if the regular verbs in our matched subset contained a fair number of such items, this might be expected to reduce the overall advantage for irregular items.

To assess this possibility, we divided the 34 regular verbs in our matched target set into those without a rhyming irregular ($N = 15$, e.g., *seem, drop*) and those with an irregular neighbour ($N = 19$, e.g., *live* which rhymes with the irregular *give*; *play* which rhymes with *say*). The non-rhyming regular past forms were significantly longer (mean = 4.2 phonemes) than the rhyming inconsistent regulars (mean = 3.6 phonemes), $t(32) = 3.06$, $p < .01$, so the impact of this variable will have to be considered via regression analyses.

For sentence completion, performance was numerically though not significantly better in the direction predicted by the dual-mechanism theory, with mean proportions of .32 and .26, respectively, on rhyme vs non-rhyme regulars: by subjects, $t(8) = 1.4$, $p = .20$; by items, $t(32) = 1.43$, $p = .16$. In a multiple regression with phoneme length entered, the t value for the by-items analysis reduces to 0.29, $p = .78$. Reading accuracy was, as usual, low, but it was also very similar on regular past-tense forms that do (.28) and do not (.26) have rhyming irregular neighbours, $t(9$, by subjects$) = 0.64$, $p = .54$; $t(32$, by items$) = 0.34$, $p = .74$. Rhyme status did, however, have an impact on repetition in the predicted direction: .73 on the rhyming subset vs .55 on the non-rhyme items, a significant effect both by subjects and by items that survived the regression analysis with phoneme length included (by items, $p = .02$). Surprisingly, the patients were even more successful at repeating inconsistent regular past-tense forms (.73) than irregular past-tense verbs (.65), although this advantage does not achieve significance once phoneme length is accounted for in a regression analysis. Most critically, perhaps, from the point of view of the prediction of the dual-mechanism account: if we compare past-tense repetition performance between non-rhyme regulars and the irregular verbs matched to these in our set, the by-items analysis yields a non-significant result, $t = 1.28$, $p = .21$.

To summarise: we have performed several further comparisons within our regular and irregular target sets that were designed to test specific predictions from the dual mechanism account. The outcomes were: no statistically significant disadvantage for irregular verbs that 'resemble' regulars by virtue of the addition of [d] or [t] in the past-tense form, in any of the three tasks; and no significant advantage for inconsistent regular verbs that 'resemble' irregulars by virtue of a having a rhyming irregular neighbour, in either sentence completion or reading. There was a sizeable advantage for inconsistent > consistent regulars in repetition; but the consistent items, whose past-tense forms presumably do not require lexical representation, did not yield significantly lower past-tense repetition scores than their matched irregular verbs.

Different allophones of -ed

We analysed the patients' performance on the three subsets of regular verbs that varied in the phonological realization of the regular past-tense ending ([t], [d], [ɪd]) but were matched for frequency, imageability and CV structure of the stem. The results of this manipulation are displayed in Table 6. There was no reliable impact of regular ending type in either sentence completion or reading, but ANOVA for repetition yielded a highly significant effect, $F(2, 18) = 17.7$, $p < .001$. Two further repeated measures t tests demonstrated that success in repeating items ending in [ɪd] (*like faded* or *hated*) was significantly higher relative to both [t] endings ($t(9) = 4.92$, $p = .001$) and [d] endings ($t(9) = 5.68$, $p < .001$). That this effect was manifested only in repetition suggests that it might be largely receptive in origin.

Table 6
Mean proportions correct on matched subsets of regular verbs ($N = 28$/subset) with the [t], [d] and [ɪd] allomorphs in each of the three tasks

	Sentence	Repetition	Reading
[t]	.32	.38	.26
[d]	.27	.45	.25
[ɪd]	.24	.68	.31

Full stimulus set

All available scores for the full set of 252 past tense verbs ($N = 6$ patients for sentence completion, $N = 10$ for both reading and repetition) were combined to enable a multiple regression analysis for each production task. The following variables were entered (with the exception of imageability, where ratings are only available for uninflected verb forms, the variable always applies to the past-tense form): number of phonemes, number of syllables, number of consonants at onset, number of consonants at offset, imageability, frequency, whether the word is a homograph, and whether it is regular or irregular. The results of these regression analyses, for each of the three tasks on 252 stimulus items, are displayed in Table 7. In sentence completion, perhaps because performance was so poor across the board (and only six patients' data were available), no variable reached conventional levels of significance; the two factors closest to reliability were the frequency of the past-tense form (higher frequency → better performance) and the number of phonemes it contains (more phonemes → worse performance). Regularity status did not approach significance and indeed, as for the matched subset, went slightly in the direction of better performance for regular verbs (a negative t-value in Table 7). For repetition, two variables were significant predictors of success: past-tense frequency (higher → better) and the number of consonants at the end of the target word (more → worse). Two further factors had borderline effects, with a small disadvantage for items with more consonants at the beginning of the word, and a small advantage for irregular verbs. Reading once again produced a different pattern of results. Frequency

Table 7
The *t* statistic values and associated probability values for 8 factors in a regression analyses on the full $N = 252$ past-tense verbs in each of the three production tasks. All factors with the exception of imageability (where ratings are only available for the stem) refer to the past-tense form of the verb

	Sentence		Repetition		Reading	
	t	*p*	*t*	*p*	*t*	*p*
Frequency	1.69	0.09	3.39	0.001	4.85	0.001
No. phonemes	−1.72	0.09	−0.66	0.51	1.56	0.12
No. consonants: start	0.47	0.64	−1.78	0.08	−3.21	0.002
No. consonants: end	0.69	0.49	−2.04	0.04	−1.02	0.31
No. syllables	0.53	0.60	1.38	0.17	−0.81	0.42
Imageability	1.63	0.11	1.45	0.15	2.57	0.01
Homograph?	0.43	0.67	−0.36	0.72	1.32	0.19
Irregular?	−0.68	0.50	1.82	0.07	4.16	0.001

of the past-tense form was (as for repetition) the most powerful predictor, but an additional three variables had a highly reliable effect: more consonants at the beginning of the word to be read were harmful; higher imageability of the target word was helpful; and irregular verbs engendered better reading performance.

The significant effect of regularity for reading, even with other factors like homograph status and various phonological measures entered into the analysis, may still derive in large part from the issue discussed earlier for reading performance in the matched subset, namely the susceptibility of regular past-tense forms to visual errors like *flowed* → "flower". The nearly significant effect of regularity in the repetition task, however, cannot be explained by such a factor and thus requires comment. We will defer consideration of this effect until after Experiment 3: the fact that it applied to repetition but not sentence completion suggests that it may have originated in receptive phonology, and Experiment 3—which addresses the patients' problems in receptive phonology—will provide a better context for discussion of the regularity effect in repetition.

Experiment 3: Receptive phonology

The purpose of Experiment 3 was to assess the patients' receptive processing of past-tense verbs and other phonologically similar words. An auditory same/different judgment task was designed to answer three questions:

1. Do these patients have difficulty differentiating the spoken form of a regular past-tense verb from its stem form (e.g., *pray* versus *prayed*)?
2. If so, do they have similar problems differentiating between non-morphologically related word pairs for which the phonological difference is identical to present/past tense regular verbs (e.g., *tray* versus *trade*)?
3. Is any difficulty in detecting the presence/absence of final alveolar stops augmented by consistency between voicing of the alveolar and of the preceding phoneme? In other words, is it easier to discriminate cases with inconsistent voicing (e.g., *an/ant, he/heat or heed/heat*), than pairs with consistent voicing (e.g., *he/heed* or *an/and*)?

Question 1 speaks to the issue of whether the patients' difficulty in producing regular past tense verbs, whatever its eventual complete explanation, extends to speech perception and comprehension. Question 2 addresses the hypothesis that any difficulties in detecting the presence of the final alveolar stop on a regular past-tense form might again be due to a general phonological deficit rather than a specific morphological impairment. Question 3 has implications for irregular verbs such as *send* and *bend*. The past-tense forms of such verbs also have final alveolar stops, but unlike all regular past tense forms of this type (e.g., *own/owned, grin/grinned*), the final /t/ of *sent* and *bent* is unvoiced, even though the preceding nasal consonant is voiced. This difference might make it easier to discriminate between the stem and past tense of irregular verbs like *send* and *sent* than between stem and past tense forms of regular verbs like *pen* and *penned*.

Methods

Participants

The participants for this experiment were the 10 nonfluent aphasic patients described above, plus 10 normal control participants from the MRC Cognition and Brain Sciences Unit volunteer panel. The patients had been given audiograms, and some were found to have significant age-related sensory hearing impairments; in one case (MB) this was severe. From a larger set of normal subjects also given audiometric testing, 10 controls were therefore chosen to match the patients as closely as possible not only for age (control mean = 64.0, range from 53 to 83) but also for hearing acuity.

Materials

A set of materials was constructed incorporating 38 pairs which were stem and past-tense forms of regular verbs (e.g., *press/pressed*) matched to word pairs which were semantically distinct but which had the same phonological distinction between the pair (e.g., *chess/chest*). These pairs, which were matched as closely as possible for word frequency and imageability, are listed in Appendix D. Also included were 125 word pairs (which were not verbs) in which the final alveolar could be manipulated but still provide real English words (e.g., *an/and, an/ant, and/ant*). Each word in the set was recorded individually onto digital tape in a sound-proofed studio by a male and a female speaker, and each pair to be judged consisted of one word in the male voice and the other in the female voice, so that the subjects would not be able to judge pairs merely on the basis of acoustic similarity. The digitised words were transformed into sound files for manipulation using Syntrillium CoolEdit software. The experiment was designed so that each different pair would be presented twice, once each way round (e.g., *press/pressed* and *pressed/press*). Each identity version within a pair was presented once (e.g., *press/press* and *pressed/pressed*). This would have provided an equal number of same and different pairs in the set, but the inclusion of triads of items such as the *an/and/ant* manipulation, which provided six different pairs and only three same pairs, meant that the complete set comprised 60% different pairs and 40% same pairs. For all pairs, the female voice preceded the male voice version. The list was pseudo-randomised and divided into four blocks for presentation. The same word pair (albeit in reverse order) was never presented twice in the same block. Each sound file was copied with a one second pause between members of the same pair and a three second pause after each word pair. Six practice pairs were also recorded, using words that did not appear in the stimulus set.

Procedure

Subjects listened to the stimuli over headphones and responded by pointing to cards with the words *same* or *different* to indicate whether they thought the two words spoken by the female and male voice were the same or not.

Results

Control subjects, regardless of hearing impairment, performed essentially at ceiling: mean proportions correct = 0.97 ($SD = 0.02$) on same trials, 0.99 ($SD = 0.01$) on different trials. The patients performed relatively well on the same trials (mean proportion correct = 0.91, $SD = 0.07$), such that their overall scores on the test were well above chance; but success on different trials averaged only 0.62 ($SD = 0.16$); the following analyses concern only the responses to different pairs. Fig. 3 shows that, with the exception of JL, all patients were impaired at discriminating regular stems from their past-tense forms, but that performance was equally poor for detecting the difference between pairs such as *chess* and *chest*. The mean proportions correct in these two conditions were .54 and .55 respectively ($t(9) = -.677$, ns). This pair of findings provides the answers to questions 1 and 2: it appears that impairment to phonological processes may be sufficient to explain the difficulty in discriminating these fine phonemic contrasts, a difficulty that is clearly not limited to morphological contrasts.

Fig. 4 displays the results for the different types of contrasts. In this analysis the results for the stem/past-tense verb pairs have been combined with those of their phonologically matched morphologically distinct pairs, as there was no discrepancy in performance between the

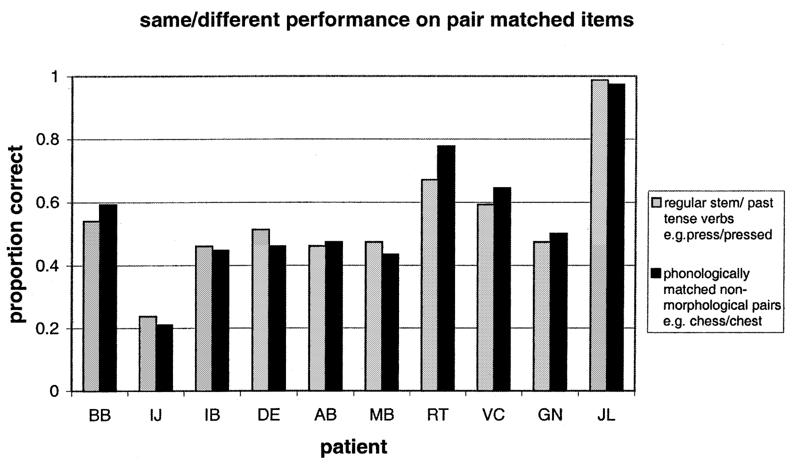

Fig. 3. Performance on the same/different auditory judgment task: Proportion of correct responses by each patient on 'different' trials composed of either regular verb stems and their past-tense forms or phonologically matched non-morphological word pairs. Note that each proportion is out of a total of 76, because the 38 pairs in each condition were presented twice—once in each order (e.g., *chess* before and after *chest*).

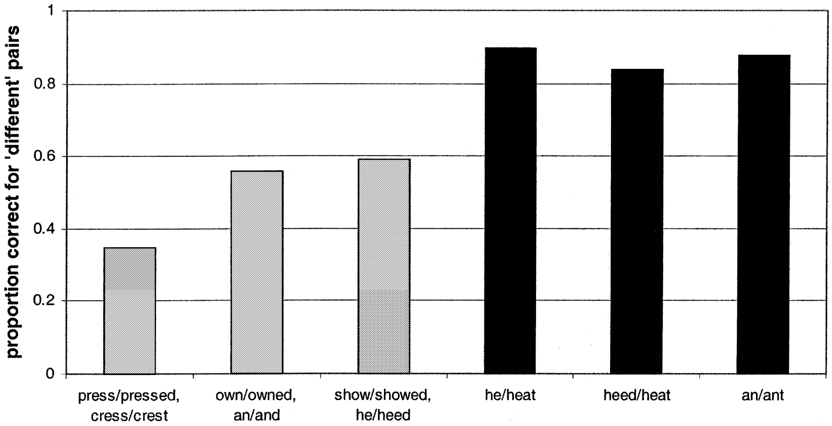

Fig. 4. Performance on the same/different auditory judgment task: Average proportion of correct responses on 'different' trials with varying contrasts.

two conditions. Fig. 4 indicates that the pairs most likely to go undetected as different were those for which voicing is consistent across final and penultimate phoneme (the light grey bars). This is true whether the pairs were stem and past tense of the same verb (such as *chase/chased, own/owned*) or two distinct words (such as *chess/chest*; *an/and*). Detection of a difference was much better for word pairs that also differ by only the final phoneme but for which—as in *an/ant*—the final phoneme is unvoiced and the penultimate phoneme is voiced (the black bars) (note that the reverse is not possible in English). This advantage in accuracy for the black-bar over the grey-bar conditions is highly significant ($t(9) = 6.71$, $p < .001$). The patients seemed to have greater difficulty discriminating pairs with unvoiced than voiced final alveolars, but there were only six possible manipulations of the unvoiced type, so the data set is very small, and there was no pair-wise matching across the voicing contrast.

Even though control subjects made very few errors, the occasional differences that they failed to detect were also more likely to be on pairs in which the word with the extra phoneme had consistency of voicing, The pattern observed in the patient group is therefore a much exaggerated normal pattern: it is easier to perceive the difference between *he* and *heat* than between *he* and *heed.* Fig. 5 shows the acoustic difference between the words *he, heed* and *heat* by means of spectrograms of these words spoken by the same male speaker. Not only is the vowel in *heat* shorter, but there is an approximately 14 ms period between the offset of voicing and the final stop. This contrast has been noted previously with regard to final fricatives in English by Massaro (1987).

To summarise, the results provide a positive answer to all three questions posed by this experiment: these patients do have difficulty hearing the difference between spoken tokens of a regular verb stem and its past tense; they have an identically high rate of error in differentiating morphologically unrelated spoken word pairs for which the phonological difference is identical to stem/past tense regular verbs; and their success in detecting the difference associated with final alveolar stops is significantly predicted by the consistency of voicing of the preceding phoneme. In other words, the patients are very poor at discriminating between stem and past-tense forms of regular verbs; but at least on the basis of the evidence presented here, the source of this deficit appears to be phonological, not morphological.

The reason for the caveat "at least on the basis of..." in the last sentence is that, since we completed this study, Tyler, Randall, and Marslen-Wilson (2002b) have published the results of an almost identical same/different receptive task in nonfluent aphasic patients ($N = 4$), but measuring response times (RTs) as well as accuracy of such judgments. Tyler et al. also incorporated some kinds of materials for same/different judgments that we did not (and vice versa), but both studies included the critical contrast of regular verb stems and past-tense forms (e.g., *pray/prayed*) with phonologically matched non-morphological cases (*tray/trade*). With regard to judgment accuracy, results from the two studies for this important contrast more or less coincide: the different-judgment scores for the patients studied by Tyler et al., although not quite as poor as those of our patients, were significantly impaired, and about equally so, in both of these conditions: 31% error for regular stem versus past and 25% error for the non-morphological phonologically matched condition, a non-significant difference. Because the patients' correct responses were significantly slower in the former than the latter condition, however, these authors concluded that an impairment in

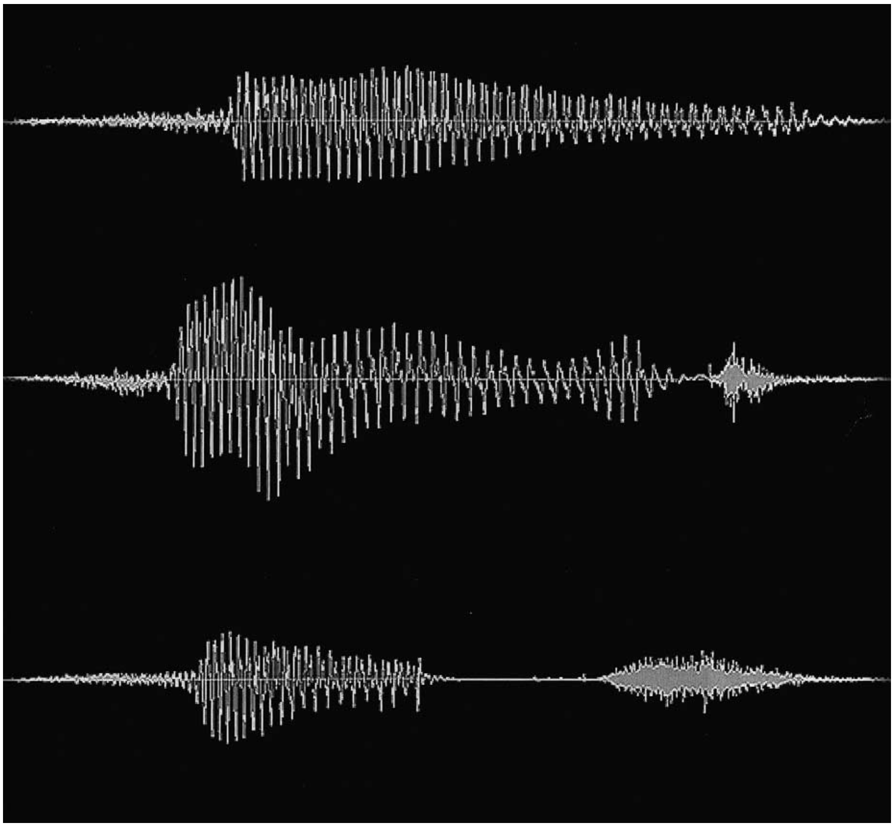

Fig. 5. Spectrograms of the spoken words *he*, *heed*, and *heat*.

processing the regular past tense cannot be reduced to a deficit in phonological processing, but requires additional explanation in terms of morphological processing. We did not measure RTs, and therefore cannot judge whether our patients, and in particular our materials, would have produced a similar outcome in this regard. Whether there is a true discrepancy between these two sets of results will need to be determined by future studies that consider the properties of the stimuli and measures.

With this new insight into the patients' considerable impairment of phonological processing in a purely receptive task, we can now return to the nearly-significant regularity effect in past-tense repetition observed in the regression analysis of the full stimulus set in Experiment 2 (Table 7). In all monosyllabic regular past-tense forms, the added alveolar stop is consistent in voicing with the previous phoneme (e.g., "owned"); in the set of monosyllabic irregular past-tense forms, some pairs of terminal phonemes do and some do not have voicing consistency (e.g., "held" versus "felt", respectively). The results of Experiment 3, which demonstrate a major impact of this variable in receptive processing, thus suggest another possible interpretation of the regularity effect in repetition in Experiment 2: that repetition of regular past-tense forms by these patients is disadvantaged by the fact that all regular past-tense forms of words not already ending in [d] or [t] exhibit voicing consistency. In the full set of stimulus materials for Experiment 2, voicing consistency characterizes all 98 monosyllabic past tense regular verbs but only 69 irregular verbs. When the same regression analysis as the one performed earlier for the patients' repetition performance on the whole set of materials is applied to repetition of only those monosyllabic regular and irregular past tenses that exhibit voicing consistency, the borderline-significant effect of regularity reported in Table 7 ($t = 1.82$, $p = .07$) is reduced to non-significance, $t(159) = 0.84$, $p = .40$. We therefore conclude that repetition of past-tense forms was not significantly affected by regularity status per se.

Experiment 4: A brief addendum on the other side of the double dissociation

Five patients with semantic dementia were tested in the sentence completion task on the main set of verb

Table 8
Proportion correct responses from five SD patients in the sentence completion task

	AN	EK	AT	WM	MK	Mean
High frequency regular verbs ($N = 63$)	1.0	1.0	.97	1.0	.94	.98
Low frequency regular verbs ($N = 63$)	.98	.92	.97	1.0	.87	.95
High frequency irregular verbs ($N = 63$)	.95	.94	.86	.89	.33	.79
Low frequency irregular verbs ($N = 63$)	.83	.60	.48	.32	.16	.48
Regular verbs matched for CV structure ($N = 34$)	1.0	1.0	1.0	1.0	.88	.98
Irregular verbs matched for CV structure ($N = 34$)	.97	.74	.53	.59	.09	.58

materials employed in this study, in order to establish that semantically impaired individuals would exhibit the same regular > irregular advantage with these new materials as previously reported by Patterson et al. (2001). Two of these patients (AT and WM) had taken part in the previous study. The procedure was exactly the same as for sentence completion in Experiments 1 and 2. Table 8 displays performance on the full set of 252 items, divided by regularity and frequency, and also on the balanced subsets of items. The data clearly establish the same regularity-by-frequency interaction in past-tense generation as was previously documented, with a strong disadvantage for irregular verbs, in particular those of low frequency; ANOVA yields significant main effects for both variables plus a significant interaction (frequency: $F(1,4) = 22.2$, $p < .01$; regularity: $F(1,4) = 11.6$, $p < .05$; interaction: $F(1,4) = 9.99$, $p < .05$). This regularity effect is maintained in the subsets of regular and irregular verbs matched for frequency, imageability and CV structure ($t(4) = 3.13$, $p < .04$).

The large regularity-by-frequency interaction in semantically impaired patients, which is a massive augmentation (and measured in accuracy) of the significant regularity-by-frequency interaction observed in reaction times when normal speakers are asked to transform verb stems to past tense (Daugherty & Seidenberg, 1992; Seidenberg, 1992), is predicted by both major accounts of impairments in past-tense generation. Likewise, the fact that errors in generating the past tense of irregular verbs were predominantly regularizations (e.g., *grinded*) is consistent with both accounts; this error type accounted for 66% of all five patients' errors combined. The most severely impaired patients (MK, AT and WM) sometimes also repeated the stem form, accounting for 19% of the total errors. Verbs whose stems end in *-ing*, a considerable quasi-regular subset of irregular verbs, yielded 6% of the total errors. The responses were all instances of incorrect application of the transformation appropriate either to *sing* → *sang* (e.g., *swing* → *swang*) or to *sting* → *stung* (e.g., *bring* → *brung*). Even more interesting are the errors on regular verbs in which phonological transformations appropriate to irregular verbs are used. Examples from these five SD patients include *blink* → *blank*, *reap* → *rept* and *creak* → *croke* (compare *drink* → *drank*, *weep* → *wept* and *speak* → *spoke*). Such errors suggest that these patients apply their remaining knowledge of the way in which past tenses of verbs are formed through phonological transformations, and that this knowledge base includes irregular forms as well as the overwhelmingly common *-ed*.

General discussion

Neuropsychological dissociations between regular and irregular past tense verb processing have been explained in two basic ways: (a) separate mechanisms comprising a rule-governed process for regular verbs and a lexical-associative process for irregular verbs, which can be independently disrupted by brain damage; (b) a single system for all verbs in which damage to the phonological or semantic component of the language system has differential consequences for regular versus irregular verbs. We now discuss how the studies described here contribute to this debate, starting with a brief summary of the main findings.

(a) On a screening test with materials similar to (in fact incorporating) the items used by Ullman et al. (1997, in press), the patients in this study displayed a significant irregular > regular advantage for producing the past tense of verbs in three different tasks. This result can be interpreted by either theory.
(b) In line with the single mechanism account, we expected these patients to have phonological deficits across a variety of tasks, and indeed all 10 patients meeting our verb criteria on screening assessments were impaired on tests of both receptive and productive phonology: digit span, rhyme judgment, rhyme production and phoneme segmentation/blending.
(c) When samples of regular and irregular past-tense verbs were subsequently matched for phonological structure, the previously obtained significant irregular > regular advantage was eliminated in the tasks of sentence completion and repetition, and

was reduced to borderline significance in reading when homograph status of the items was factored into the analysis. The absence of any substantial impact of regularity on success with phonologically matched verbs was a direct prediction of the single-mechanism account, whereas the dual mechanism theory would presumably still anticipate a significant irregular advantage even with such materials.

(d) We further demonstrated, with analyses dividing the regular verbs in our matched subset into those with/without rhyming irregular neighbours, and the irregular verbs in our matched subset into those with/without affix-like past-tense endings, that neither of these factors is likely to explain the change in outcome from the screening test to the phonologically matched materials for either sentence completion, or reading. The presence/absence of affix-like endings also had no impact on success in repetition, but 'inconsistent' regulars whose stems rhyme with irregular verbs resulted in unexpectedly good repetition performance. There was, however, no significant disadvantage in repetition for the past-tense forms of consistent (non-rhyming) regulars relative to matched irregular items.

(e) Apart from the embedded matched subset of 68 (34 pairs of) regular/irregular verbs, the 252 verbs in the full set of materials were not controlled for phonological complexity. We therefore might have expected the patients' performance on the full set to be characterized by the significant irregular > regular pattern observed in our screening test. For sentence completion—the task that most obviously requires the speaker to transform a verb from stem to past-tense form—regularity had no impact on success in the full set of 252 verbs. The only near-significant factors were word frequency and number of phonemes in the past-tense verb. This outcome suggests some fragility of the irregular > regular pattern even on materials that are not carefully matched. An advantage for irregular > regular did apply to reading, along with three other additional significant predictors of success: word frequency, imageability, and the number of consonants at the beginning of the word. For repetition, there were reliable effects of both frequency and number of word-final consonants and borderline effects of both the number of word-initial consonants and regularity. The effect of regularity was eliminated in a subsequent regression analysis controlling for voicing consistency of the terminal phonemes in past-tense forms; this variable appears to have a substantial impact on receptive phonological abilities of patients with Broca's aphasia.

(f) In a receptive task requiring same/different judgments on spoken pairs of words (in two different voices), the patients' overall performance was well above chance because of high rates of correct "yes" responses to same pairs; but in the critical conditions of different pairs, they achieved very low scores for detecting the difference between regular verb stems and their past-tense forms (e.g., *press/pressed:* average proportion correct 0.54) but equally poor scores for phonologically matched non-morphological contrasts (e.g., *chess/chest:* average proportion correct 0.55). In all contrasts included in this experiment, accuracy of different judgments was significantly lower when voicing was consistent between the penultimate and final phonemes of the longer word (e.g., *own/owned* or *an/and* than for pairs where the longer word ends with inconsistent voicing (e.g., *an/ant*). The strength of this effect is another indication that the explanation for a regular past-tense deficit may lie in phonological rather than (or at least in addition to) morphological processing: consistency of voicing between a final alveolar stop and its preceding phoneme, which creates the difficult-to-detect case, always applies to regular past-tense forms.

(g) As a brief check on the robustness of the other side of the dissociation, we replicated—on the materials used here with nonfluent patients—the highly reliable regular > irregular past-tense effect in sentence completion previously documented for semantically impaired patients (Patterson et al., 2001; Ullman et al., 1997).

Prior to this study, there has been a relative paucity of evidence for a reliable impairment on regular relative to irregular past tense verbs in the sphere of past tense production. With the exception of the nonfluent aphasic patient FCL (studied by Ullman et al., 1997, in press), who was able to perform the past-tense sentence completion task and showed a substantial advantage for irregular verbs, the majority of such reported effects have been limited to reading tasks, although deficits have also been noted in writing and repetition; see Ullman (1999, in press). A more major source of evidence has come from receptive tasks. In addition to the same/different receptive findings published by Tyler et al. (2002b) and already mentioned above in the comments on our own findings with this task, Marslen-Wilson & Tyler (1997, 1998) and Tyler et al. (2002a) have reported results from a task of primed auditory lexical decision with nonfluent aphasic patients and normal controls. The controls showed significant facilitation (faster RTs) when a verb stem was primed by its past tense for both regular and irregular conditions (e.g., *saved-save, gave-give*); by contrast, the performance of the aphasic patients was facilitated to a normal degree in the irregular condition but not at all (indeed lexical decision RTs were prolonged) in the regular condition. The substantial error rate of nonfluent aphasics (not only the patients in this study but also those in Tyler et al., 2002b) when asked to detect the difference between spoken pairs like *saved-save* leads one to expect that, when such patients are presented with the prime *saved* and then immediately asked to make a lexical decision to *save*, the two stimuli might be perceived as identical and hence result in repetition priming. It is therefore puzzling to us that, in this condition of Marslen-Wilson & Tyler's (1997) experiment, the nonfluent patients' RTs were slowed.

In another receptive task, Ullman et al. (in press) reported an advantage for irregular past tense verbs when nonfluent aphasic patients were asked to judge the acceptability of correct and incorrect forms in sentences. Patients received simultaneous written and spoken presentation of the same sentences as had been used in the sentence completion paradigm, but the verb was either the correct past tense form or an incorrect alternative. For regular verbs, the incorrect form was the uninflected stem of the verb; for irregular verbs, the incorrect form was a regularised form (e.g., *digged*). Patients were asked to rate how good or bad the verb form was, or say whether the target was acceptable. Two of the three patients tested (FCL and BMC) chose more correct irregular than correct regular forms, and also incorrectly accepted as an appropriate past tense more regular stem forms than regularised irregular verbs. The third patient (RBA) showed these effects only in RT data, not in accuracy.

Once again the outcome of our studies suggests a possible alternative interpretation of this result. The higher error rate or slowed responses to correct past tense forms and to incorrect stem forms of regular verbs might have arisen because the patients found it difficult to distinguish between the two. For irregular verbs, the correct past tense forms were phonologically (and orthographically) much more distinct from their uninflected counterparts, enabling the patients to be more often sure of what they had heard. Because the incorrect form offered for the irregular verbs in the Ullman et al. experiment was a regularisation (e.g., *digged*), one might have thought that we would expect the patients to perceive this as *dig* and thus predict more impairment in this condition than was observed. It is worth noting, however, that while all 20 of the regular past-tense verb stimuli in the judgment experiment were single-syllable words (e.g., *slammed*), 5 out of the 16 irregular verbs, when regularised, formed two-syllable words (e.g., *standed*). When the addition of *-ed* to a regular verb results in an extra syllable, the patients in our study were significantly more successful in the repetition of the regular past tense, which we interpreted as indicative of better perception of these items. This is yet another possible non-morphological factor that might be germane to the finding by Ullman et al. (in press) of more successful (or quicker) rejections of the incorrect alternatives for irregular than verbs.

Three issues raised by our study remain to be addressed, though none of them currently yields to full resolution. (1) Why is reading different? (2) How comparable are the patients in our sample to those reported in other studies of past-tense verb processing in nonfluent aphasia? (3) What do we mean by a phonological deficit?

Reading aloud of past-tense verbs does not have equivalent face validity to the sentence completion task for assessing productive knowledge of past-tense forms; but it is the task for which the pattern irregular > regular has been most often reported and most robust in previous studies of verb production by nonfluent patients. In papers by Ullman et al. (1997, in press), the authors' motivation for use of the reading task was partly that so few members of their patient group were able to perform sentence completion. Our results, however, suggest: (a) that reading is more likely than sentence completion to yield a past-tense irregular advantage, but (b) that it is also subject to confounds of which investigators must be wary. As indicated earlier, one potential confound derives from the fact that some irregular past tense forms are homographs of other more concrete words (e.g., *ground*, the past tense of *grind*, is also a noun referring to the surface of the earth). Because the oral reading performance of all of the patients studied here, in keeping with other nonfluent agrammatic patients reported in the literature, was characterised by a strong advantage for high > low imageability words, this more concrete meaning for *ground* confers a degree of benefit to reading such words that were intended (but perhaps unbeknownst to the patients!) to refer to past-tense verbs. Inclusion of homograph status in a regression analysis on our balanced subset of items did reduce the irregular advantage in reading from high to borderline significance. But the same was not true for the regression analysis of the irregular verbs in our full set of 252 items, so this factor is clearly not the whole story.

Also as indicated earlier, regular past-tense forms are probably at an extra disadvantage in reading because of the lure of orthographically similar neighbours. These include not only the stem form (*flowed* resembles *flow* much more than *thought* resembles *think*) but also *-er* noun forms, many of which are more concrete than the past-tense verbs that they resemble (compare *flowed with flower, towed* with *tower* and *sewed* with *sewer*). All of these *-er* words were fairly common error responses to past-tense regular verbs in our data. It is possible that a combination of homograph status and orthographic similarity, along with other potentially confounding factors specific to reading, will turn out to be sufficient to explain the tendency for the reading task to reveal an irregular > regular pattern; but as yet we probably do not have a complete grasp of all of the factors leading to these task differences.

The second discussion point is the issue of whether the difference between our findings and those of Ullman et al. (1997, in press) might be attributable to differences in patient samples. Even though all of the patients in both studies are described as nonfluent aphasics, they would inevitably differ somewhat in lesion size, precise lesion location, and the behavioural/linguistic consequences of the lesions. How confident can we be in generalising our results to a prediction about the performance of a different patient sample?

The first point to note is that even the nonfluent patients described by Ullman et al. (1997, in press) were a heterogeneous set, and furthermore were not all tested on the same tasks. Of the two who were able to perform the sentence completion task (FCL and RBA), only FCL achieved the predicted significant advantage for irregular verbs in this task. Furthermore, on the reading task for which all of the patients did provide data and where there was a significant group pattern of irregular > regular, FCL's irregular advantage was not significant. We mention these facts not to comment on the strength of the reported effects in the studies of Ullman et al. but simply to emphasise the difficulty of comparisons of outcomes across different patients, even within a single study.

Examination of error types can sometimes be illuminating in such circumstances. Ullman et al. (in press) provide a detailed description of errors (in the sentence completion task for two cases, FCL and RBA, and in the reading task for nine patients), enabling us to classify these in the same manner as we have done for errors in Table 5. Perhaps the major difference in both tasks is that our cases seem to have made a higher proportion of errors so discrepant from the target word that these could only be classified as *other*; this perhaps suggests, on average, a more severe phonological deficit in our sample (although the inability of the majority of their cases to respond much at all in the sentence completion task might suggest the reverse). But in other regards, the error pattern is very similar, with all patients producing both stem (unmarked) and morphological (mainly *-ing*) errors as well as substituting other phonologically and/or orthographically similar words for the targets.

Although there is no completely satisfactory way to resolve the problem of comparison across studies of different patients, we see no basis for assuming qualitative differences between our cases and theirs. In our sentence completion screening task which incorporated the materials from Ullman et al. (1997), the irregular > regular advantage for case GN was substantial (see Fig. 1), even if not quite as large as that reported by Ullman et al. for patient FCL. Fig. 6 demonstrates that GN's lesion was also very similar to that of FCL: both had large left frontal infarcts affecting the region around Broca's area, including the frontal operculum, middle and inferior frontal gyri and insula; in both cases, parietal and temporal lobes remained essentially intact. On the basis of both the neuroradiological and behavioural similarities, we predict—but of course cannot be sure—that the elimination of the irregular advantage observed for GN when stimulus words were controlled for phonological structure would also characterize FCL if tested on the same materials.

Finally, we have proposed that deficits in the processing of regular past tense verbs arise from a phonological deficit. It is important to note in this regard that we screened many patients ($N = 50$) clinically diagnosed as 'nonfluent', all of whom presumably had phonological deficits, but most of whom did not show a consistent advantage for the irregular past tense across the three production tasks. Why might this be? One reason is that many of these patients had such

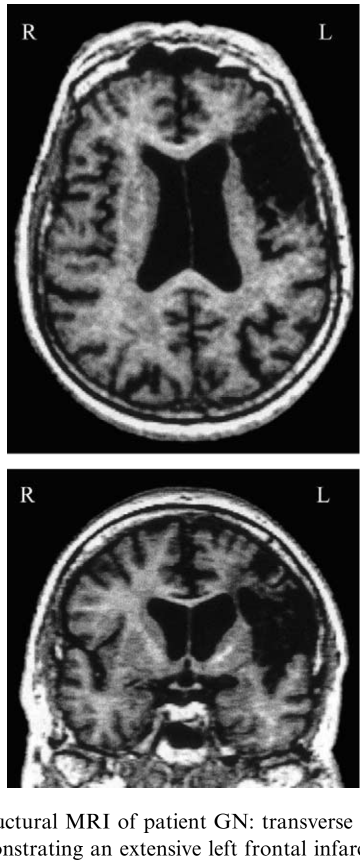

Fig. 6. Structural MRI of patient GN: transverse and coronal views demonstrating an extensive left frontal infarct.

severe expressive aphasia that they were unable to cope with the sentence completion task. Some of these patients also had varying degrees of accompanying oral apraxia, which clearly will affect articulation. More interesting is the question of exactly what is meant by a phonological deficit, and whether the precise nature of the impairment may differ even across cases who perform similarly on some tests. Even if there is some validity to our hypothesis that a phonological deficit is central to difficulty in regular past tense processing, we are inclined to doubt that we will be able to discover or invent a simple measure of 'phonological deficit' that can be correlated straightforwardly with degree of success/failure on verb tests.

Our critical production materials were designed only to equate the number of consonants within clusters across regular and irregular items. The same-different phonological judgment experiment, however, demonstrated clearly that the kinds of phonemes that cluster together are vitally important in perception, at least with regard to consistency of voicing. Whether the actual content of phoneme clusters also significantly modulates production difficulty is yet to be determined, although we anticipate that there will be such effects. And there is yet another phonological difference between the regular and irregular past tense in English, which we have not considered here: the types of vowels that they include. In monosyllabic regular past-tense forms, the phoneme preceding the final alveolar stop is always either another consonant (*slipped*) or a long vowel (*booed*) or a diphthong (*showed*). In many cases, these are even combined, i.e., a long vowel or diphthong followed by a stop consonant followed by the final alveolar, as in *piped* or *streaked*. While some irregular past tense forms have long vowels followed by a stop (*strode*) and others end in two stops (*kept*), none contain a long vowel followed by two stops as in *beeped*; indeed, few if any words in English at all, apart from regular past-tense forms, have this structure, which is why Burzio (2002) describes such words as morphologically regular but phonologically highly irregular. Stemberger & Middleton (in press) also provide evidence for the importance of vowel dominance in determining both regularization and overtensing errors by normal speakers (an example of an overtensing error is an incorrect utterance like "didn't drank" in place of "didn't drink").

In summary, despite several unresolved issues concerning the precise nature of the phonological deficits critical to our account, we contend that the data presented here provide novel and compelling evidence that deficits on regular past tense verbs might be explained by phonological factors and without recourse to a separate rule-based mechanism. The two critical results are: (a) that a significant irregular > regular advantage across three production tasks (sentence completion, repetition, oral reading) in screening tests was subsequently reduced or even eliminated by phonological matching of the CV structure of regular and irregular past tense forms; and (b) that a significant deficit in judging as different the spoken forms of stem and past-tense regular verbs (*press/pressed*) applied equally to phonologically identical but non-morphological contrasts (*chess/chest*). Our interpretation invokes phonological impairment as the basis of poorer performance for the regular past tense, due to its greater phonological complexity, and our neuropsychological data have demonstrated the link between these phenomena. These data support a model in which regular and irregular past tense verbs are processed within a single system drawing on semantic and phonological knowledge.

Acknowledgments

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Appendix A. Items used in part 1 of the screening assessment

Regular verbs	Irregular verbs
step	fall
rock	eat
pass	fight
space	lead
march	rise
heat	sit
wheel	read
dust	stand
voice	speak
test	sleep
clear	cut
play	write
fork	weep
tempt	flee
graze	grind
tune	freeze
tap	leap
roar	sting
dent	lend
lace	swim
rake	slit
chew	stride
beg	steal
pour	tear

Appendix B. Subset of verbs controlled for frequency (log lemma frequency from Celex), imageability (mean rating on a 7-point scale) and CV structure

	Regular verbs				Irregular verbs		
	Frequency	Imageability	Past CV structure		Frequency	Imageability	Past CV structure
seem	2.9479	249	CVCC	mean	2.8643	207	CVCC
live	2.7180	291	CVCC	keep	2.8179	286	CVCC
name	1.7628	348	CVCC	lend	1.4355	327	CVCC
try	2.8680	362	CCVC	bring	2.7089	346	CCVC
guess	1.8873	330	CVCC	cast	1.6137	367	CVCC
use	2.9018	336	CVCC	leave	2.8936	373	CVCC
lay	2.0821	405	CVC	win	2.1874	382	CVC
show	2.6702	375	CVC	let	2.6343	383	CVC
train	1.7711	406	CCVCC	grind	1.4373	386	CCVCC
tow	0.5723	406	CVC	bid	0.6756	394	CVC
gain	1.9413	346	CVCC	bend	1.8177	395	CVCC
fail	2.1625	379	CVCC	sell	2.1605	397	CVCC
die	2.3775	395	CVC	buy	2.4084	397	CVC
pull	2.2686	405	CVCC	build	2.3833	399	CVCC
fill	2.1377	450	CVCC	deal	2.0183	421	CVCC
flow	1.5358	417	CCVC	slide	1.5428	427	CCVC
view	1.4778	413	CCVC	flee	1.4292	431	CCVC
weigh	1.4770	411	CVC	ride	1.7544	432	CVC
call	2.8406	421	CVCC	hold	2.6665	445	CVCC
sigh	1.4834	418	CVC	shake	2.1189	450	CVC
chew	1.3037	448	CVC	dig	1.6011	455	CVC
sew	1.0494	450	CVC	ring	1.9571	455	CVC
stew	0.6154	469	CCCVC	split	1.5236	459	CCCVC
play	2.6062	409	CCVC	swing	1.7466	459	CCVC
spray	1.0015	522	CCCVC	stride	1.0984	462	CCCVC
pay	2.5433	491	CVC	teach	2.1541	473	CVC
drop	2.1529	414	CCVCC	sleep	2.1091	477	CCVCC
pray	1.4495	464	CCVC	steal	1.7198	486	CCVC
cry	2.0803	523	CCVC	speak	2.5693	488	CCVC
slap	1.2160	531	CCVCC	sweep	1.7076	510	CCVCC
wipe	1.5710	529	CVCC	weep	1.4443	523	CVCC
how	0.9942	507	CVCC	wind	1.2131	535	CVCC
tie	1.7876	551	CVC	bite	1.4382	553	CVC
fry	1.3283	562	CCVC	freeze	1.6487	585	CCVC
Mean	1.8701	425		Mean	1.9265	428	
SD	0.6657	74.25		*SD*	0.5530	75.44	

Appendix C. Controlled subsets of regular verbs manipulating *-ed* allomorphs

[d]	Frequency	Imageability	[t]	Frequency	Imageability	[ɪd]	Frequency	Imageability
blame	1.6674	309	guess	1.8873	330	grant	1.6411	329
gain	1.9413	346	place	2.0020	340	hate	1.9618	336
name	1.7628	348	hope	2.3569	362	head	1.6694	340
love	2.3773	355	like	2.5137	363	tend	2.1147	340
solve	1.7184	360	pop	1.2777	382	tempt	1.2712	345
soothe	0.8601	379	creak	0.9076	393	fade	1.5544	383
beg	1.4834	390	mix	1.7052	395	treat	1.9927	389
rob	1.1645	400	switch	1.6383	397	sift	0.5975	397
train	1.7711	406	check	1.9188	401	rent	1.4622	405
save	2.0862	408	reap	0.6383	408	grunt	0.9610	409
groan	1.0472	428	shock	1.4959	413	lift	1.9443	414

Appendix C (*continued*)

[d]	Frequency	Imageability	[t]	Frequency	Imageability	[ɪd]	Frequency	Imageability
fill	2.1377	450	reach	2.4068	436	wait	2.5036	440
kill	2.3209	450	face	2.1332	442	shout	1.9234	455
file	1.3167	464	chop	1.2890	462	melt	1.3857	461
sail	1.3013	468	crush	1.3167	480	pat	1.2262	473
wail	0.9715	471	wrap	1.5435	482	mend	0.9252	483
crawl	1.4033	482	hop	0.9337	486	float	1.5134	486
frown	1.2175	486	bake	1.3725	495	glide	0.8107	487
prune	0.3994	490	mop	0.7548	502	greet	1.4936	494
bowl	1.1060	494	wreck	1.0087	508	knead	0.4622	500
howl	0.9942	507	smoke	1.6471	509	hunt	1.4572	502
jog	0.6600	510	smack	0.7756	510	chat	1.0663	508
wave	1.6563	514	splash	1.0015	512	wound	1.3936	512
scrub	1.0204	523	chase	1.3061	529	twist	1.5888	521
breathe	1.6444	525	blink	1.1371	531	sprint	0.4364	523
plunge	1.3001	548	slap	1.2160	531	plant	1.4770	542
comb	0.9476	552	shop	0.9106	557	skate	0.4274	562
grill	0.7632	558	sketch	0.7836	566	roast	0.9637	569
Mean	1.3943	451	Mean	1.4242	454	Mean	1.3652	450
SD	0.5075	70.42	*SD*	0.5349	68.70	*SD*	0.5329	72.85

Appendix D. Critical subsets of pairs for the same/different auditory receptive task

	Real Regular Verb	Real Regular Past tense		Matched word	Matched word Pseudo "Past"
1	own	owned	1	an	and
2	bowl	bowled	2	coal	cold
3	roll	rolled	3	mole	mould
4	pen	penned	4	ten	tend
5	rain	rained	5	wren	rend
6	man	manned	6	men	mend
7	tie	tied	7	buy	bide
8	lay	laid	8	fey	fade
9	tow	towed	9	go	goad
10	hoe	hoed	10	he	heed
11	woo	wooed	11	loo	lewd
12	key	keyed	12	me	mead
13	mew	mewed	13	new	nude
14	hem	hemmed	14	when	wend
15	weigh	weighed	15	ray	raid
16	vie	vied	16	rye	ride
17	vow	vowed	17	fee	feed
18	ply	plied	18	sly	slide
19	pray	prayed	19	tray	trade
20	lie	lied	20	why	wide
21	show	showed	21	high	hide
22	seal	sealed	22	feel	field
23	fan	fanned	23	fen	fend
24	shun	shunned	24	fun	fund
25	grin	grinned	25	gran	grand
26	file	filed	26	mile	mild
27	coo	cooed	27	do	dude
28	queue	queued	28	few	feud
29	die	died	29	guy	guide
30	pay	paid	30	jay	jade

Appendix D (*continued*)

	Real Regular Verb	Real Regular Past tense		Matched word	Matched word Pseudo "Past"
31	tee	teed	31	lea	lead
32	crow	crowed	32	prow	proud
33	chase	chased	33	chess	chest
34	press	pressed	34	cress	crest
35	mess	messed	35	less	lest
36	mix	mixed	36	necks	next
37	whiff	whiffed	37	riff	rift
38	cuff	cuffed	38	tough	tuft

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