



# Phonology and neuropsychology of the English past tense

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## Abstract

The double dissociation between the regular and irregular past tense in English has been explained in terms of dual and single mechanism accounts. In previous research we have argued that problems with the regular past tense in patients with left inferior frontal damage arise from morpho-phonological parsing difficulties [Trends in Cognitive Science 2 (1998) 428]. This claim has recently been challenged by a single mechanism connectionist account which argues that a general phonological processing deficit causes the poor performance on the regular past tense, with morphological factors playing no explicit role [Proceedings of the National Academy of Sciences 96 (1999) 7592]. We used a speeded judgement task with four patients who have documented difficulties with the regular past tense to contrast the claims made by these different approaches. We compared patients' ability to detect the difference between the past tense and stem of regular (*hugged/hug*) and irregular (*taught/teach*) past tense verbs, as well as matched "pseudo" pairs (*trade/tray* and *port/peach*). These real word conditions were accompanied by matched sets of non-words (e.g. *nugged/nug*). Patients' latencies to the regular past tense real word-pairs were consistently slower than in any other condition. To test for a general phonological processing deficit, we conducted several tests of phonological processing ability. The results show that the patients had a range of difficulties in phonological processing, from very mild to severe. This did not correlate with their performance on the speeded judgement task. We interpret this pattern of results as support for a specialised morpho-phonological processing mechanism which can be dissociated from other phonological processes and which is used directly in the processing of the regular past tense in a dual-mechanism system. © 2002 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

Recently there have been several neuropsychological studies of patient groups who have problems with either the regular (*jump-jumped*) or irregular (*teach-taught*) past tense morphology in English [7,8,18,19]. This dissociation has shown up in a variety of different tasks, such as past tense elicitation and primed lexical decision. Patients who have problems with the regulars typically show no priming for regularly inflected past tense forms and do not produce the correct form in an elicitation task. Their performance on irregulars is, however, normal. In contrast, patients who have problems with the irregulars are generally able to produce regular past tense forms without difficulty but have problems with irregularly inflected forms. They may also show significant priming effects for regularly inflected pairs but not for the irregulars. This double dissociation has been interpreted as evidence for two separate cognitive and neural

systems underlying human language function. One version of this dual-system account claims that the regulars are processed by means of a rule-based procedure which adds or strips away the past tense inflection to a stem, capturing the highly predictable mapping from stem to past tense form for the regular forms. A second system deals with the highly unpredictable irregular forms, which are learned by rote, rather than by rule, and represented in a separate knowledge store [12]. A different version of a dual-mechanism approach claims that the processing of regularly inflected past tense forms involves processes of phonological parsing [8,18] which allow identification of the stem and affix, whereas these processes do not apply to English irregular forms, which have no internal morpho-phonological structure.

The evidence for these dissociations comes from patients with damage to different neural regions. Patients with frontal damage, as a result of stroke [18] or Parkinson's disease [19] tend to have problems with the regulars. In contrast, patients with damage to inferior temporal cortex, either because they suffer from semantic dementia [7,11] Herpes Simplex Encephalitis [18] or Alzheimers disease [19], have problems

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with the irregulars. This combination of behavioural deficits and their association with damage to specific cortical regions provides clear support for two distinct systems underlying the processing of the regular and irregular past tense, and by extension, other aspects of language that can be distinguished in this way. These different systems appear to involve dissociable processing routes to lexical and semantic representations, with a temporal lobe route for access of stored whole forms (such as simple nouns and irregular past tenses), and a second route, involving frontal phonological processing systems, for complex forms such as regular past tense, where access to the stem requires processes of phonological assembly or disassembly which add or strip away the inflectional affix [8,18].

However, this type of interpretation of neurological dissociations is not without its critics from “single mechanism” connectionist perspectives, where arguments have been made on a number of grounds that behavioural dissociations do not necessarily require the postulation of distinct underlying mechanisms (e.g. [5,13]). The view that we will consider here, since it is not only directly addressed to the regular/irregular past tense distinction in English, but also places a similar emphasis to our account on the role of phonological deficits, is the model recently proposed by Joanisse and Seidenberg [4], and adopted in slightly modified form by Patterson et al. [11]. On this account, past tense dissociations are to be explained in terms of damage to a single system in which the speech input is mapped directly onto a set of distributed representations with a specific architecture of connections, modelling words in terms of their speech input, speech output, and semantics. This allows the Joanisse and Seidenberg [4] model to be trained on various tasks, including simulations of speaking, hearing, repeating and generating the past tense. Lesioning the speech output layer models a phonological deficit, which affects past tense generation performance on non-words and—at very severe levels of lesioning—on the regular past tense verbs. Lesioning the semantic layer models a semantic deficit. Here, the model performs most poorly at generating irregular past tenses. By the same token, although this was not explicitly discussed by the authors, lesioning the speech input layer should allow the system to model deficits in speech comprehension, on the same phonological basis. Whether viewed from the perspective of comprehension or of production, in neither case is there any explicit morphological differentiation between regular and irregular forms, the differences between them reflect the relative balance between semantic and phonological factors during the acquisition phase of the network.

This type of model predicts that past tense dissociations in neuropsychological patients arise from damage to either the phonological or semantic layers in a single system. If a patient has a problem with the regular past tense following brain damage, the model predicts that this will be caused by a generalised phonological processing deficit and not by damage to any system which is specifically sensitive to

morphological distinctions. The presence of a general phonological deficit will impact on the regulars more than the irregulars because processing of the regulars in speech input and output is more dependent upon the phonological relationship between the past tense and its stem. In contrast, the irregulars will be more affected by damage to semantics since the mapping from stems to irregular past tense forms is more dependent upon their semantic relationship, given the greater unpredictability of the phonological relationship between an irregular form and its stem.

Although, this type of model presents a potentially important challenge to dual route interpretations of neurological dissociations, the specific modelling results reported by Joanisse and Seidenberg [4] are not clear-cut. When the speech output layer of the model is lesioned to simulate a phonological deficit, it is the non-words that perform especially poorly, with the regulars and irregulars performing at equivalent levels and significantly better than the non-words. In additional simulations where the regulars and irregulars are matched for frequency, although there is a small advantage for the irregulars there is no indication as to whether this is statistically significant. It is only when the speech output layer is severely disrupted, by severing all connections to and from the speech cleanup layer and by adding Gaussian noise, that a clear dissociation between regulars and irregulars emerges. However, under these conditions, although the regulars perform more poorly than the irregulars, accuracy on the irregulars is also poor (between 50 and 63%). We can assume that similar outcomes would result if the lesions were applied to the speech input layer of the model, in order to model deficits in recognition of regular and irregular forms.

Putting these specific limitations to one side, this type of model makes two predictions. First, it predicts that patients who have problems with the regular past tense will have an accompanying phonological deficit, and patients who have a phonological deficit will also have problems with the regular past tense. Second, it predicts that deficits for the regulars will only occur in brain-damaged patients who have severe, as opposed to mild or moderate, degrees of phonological impairment.

A critical issue in testing these predictions is to determine what constitutes a phonological impairment. The term “phonology” is used broadly in cognitive neuropsychology to cover a range of speech analysis processes, from the primary acoustic–phonetic analysis of the incoming speech stream up to higher-level processes of segmentation, phonological parsing, and prosodic analysis. Our claim is that one basis for the dissociation between performance on regular and irregular past tense forms is a deficit in the specific class of phonological parsing mechanisms that operate on inflectionally complex words to decompose them into their constituent morphemes [8,18]. This provides the basis for further processes of functional integration with the surrounding phrasal and sentential context. In contrast, the processing of the irregular past tense does not depend on

phonological parsing to extract information about the stem and past tense marker, since irregulars are not phonologically decomposable in this way.

This account predicts that processes of morpho-phonological parsing (as distinct from more basic phonetic analysis processes) can be independently impaired following brain damage. It seems likely that damage to the L inferior frontal cortex produces this type of phonological impairment, and that this accounts for the resulting problems with the regular past tense [8,18]. The type of approach exemplified by the Joanisse and Seidenberg [4] model would not predict that there are phonological processes which are specific to morpho-phonologically complex words, since the morphological distinction between regular and irregular forms does not exist as an independent aspect of the model.

The argument that is made instead within this type of framework is that regular past tense forms are unusually phonetically complex, especially in contrast to the irregular forms, and that this makes them differentially sensitive to impairments of basic acoustic-phonetic and phonological function. It is certainly true that some regular past tense forms ending in /t/ have phonetically complex and unusual syllable codas—e.g. the [skt] sequence at the end of inflected forms such as *asked*. However, for this to explain differential impairments of regular past tense processing, the theory has to require (a) that all patients with such impairments also have generalised speech processing impairments, and (b) that performance is equally poor on control strings with matched phonological properties to the past tenses.

To test these competing accounts we selected a group of patients who had documented deficits with the regular past tense morphology, in tests of on-line processing function [18]. We tested these patients on a number of standard tests of general acoustic-phonetic and phonological function to determine whether they had impairment in these basic processes. We also developed a phonological judgement task designed to probe specifically for difficulties with higher-level processes of morpho-phonological analysis, and incorporating suitable control conditions to allow us to determine whether deficits at these levels could be attributed to more non-specific lower level deficits. This was a task in which patients listened to two speech tokens presented sequentially and decided whether the two items were different. The materials included the regular (*played/play*) and irregular (*taught/teach*) past tenses, as well as monomorphemic words that were similar in phonology to both these forms of the past tense (e.g. *trade/tray, port/peach*). There was not a complete phonological match across these real word sets, since we also wished to include the special clusters associated with past tense inflection that do not have any monomorphemic counterparts, such as the /md/ sequence in *seemed* or the /zd/ sequence in *caused*. To provide a full control for phonological complexity, we therefore also constructed sets of non-words that were matched, on a one-to-one basis, to the phonological properties of the real word past tense sets, as in pairs like *nugged/nug–thrayed/thray*.

If the patients' problems with the regular past tense originate from a general phonological processing deficit, we would expect to see difficulties in phonological processing across the board, with these difficulties being sufficient to account for any problems with regular as opposed to irregular past tenses. If, in contrast, the patients' problems with the regulars are related to specific difficulties in morpho-phonological parsing, then performance on the real regulars should be significantly impaired relative to their phonological control conditions. If the patients do have a phonological deficit, this may well have some impact on the regularly inflected past tense forms since these tend to be more phonologically complex than the irregulars. Nevertheless, we predict that such an impairment will not fully account for problems with the regulars and that a deficit for the regularly inflected past tense forms should be observed over and above any solely phonological deficit. This is the prediction we test in the first of the two studies reported below.

## 2. Patients

We tested four patients who have documented problems with the regular past tense as shown in their performance in a priming study [18] where they showed no priming for regularly inflected pairs (*jumped-jump*), but significant priming for irregularly inflected pairs (*thought-think*). This contrasts with the pattern observed in unimpaired subjects, who show priming for both regularly and irregularly inflected pairs.

The language deficits of these patients and their neuropathology have been described in detail elsewhere [17,18]. The patients are all non-fluent agrammatics. In their spoken language they omit many of the grammatical markers of speech, such as inflectional morphemes and function words and they usually have comprehension difficulties, especially when discriminating between the active and passive voice. The patients tend to show normal patterns in semantic processing. A sample of their performance on relevant language tests is given in Table 1.

1. DE is a 46-year-old right-handed man who had a CVA in 1970 following a road traffic accident. He has slow, effortful speech which contains little structure. He is both an "agrammatic" aphasic, as revealed by the BDAE and a deep dyslexic [10]. In a variety of on-line studies, he typically shows significant semantic priming effects and problems with syntax [17]. A magnetic resonance imaging (MRI) scan taken in 1996 showed extensive frontal (including Broca's area) and superior temporal damage, with sparing of the inferior temporal cortex and the right hemisphere (see Fig. 1). DE does not have a significant hearing impairment (5 dB in the left ear and 8 dB in the right ear).
2. MR is a 65-year-old right-handed woman. A MCA infarct in February 1986 left her with language abilities in both comprehension and production that are typical of

Table 1  
Background language tests on non-fluent patients: percent correct (except Ravens)

	DE	CH	MR	AS	Norms <sup>a</sup>
PALPA tests					
Single real word repetition	93	97	80	99	99
Single word reading	64	90	77	100	99
Non-word repetition	43	60	57	73	N/A
Non-word reading	4	29	42	96	95
Other tests					
Sentence repetition [16]	18	14	36	41	N/A
Syntax: spoken sentence-picture match [18]					
Reverse role	78	80	71	68	99
Lexical	100	100	92	94	
Spoken word-picture match [9]	100	100	88	100	99
Ravens CPM	36/36	34/36	25/36	32/36	29–35

<sup>a</sup> Norms taken from PALPA [6] or collected in our lab on groups of healthy subjects between 60 and 73 years, with 10–12 subjects per group.

an agrammatic aphasic. She has non-fluent speech, and difficulties with syntax, but is relatively unimpaired on semantic tests. She can repeat single words better than she can repeat sentences. Although, she shows little impairment in reading real words she has severe problems reading non-words. She has a significant hearing impairment (32 dB in the left ear and 35 dB in the right ear). A CT scan in 1996 showed a large LH infarct involving inferior frontal lobe (including Broca's area), the parietal lobe (supramarginal gyrus, paraventricular and supraventricular areas), the insula and auditory cortex, but sparing the left inferior temporal lobe (Fig. 1). The presence of aneurysm clips did not allow MR scanning.

3. CH is a 37-year-old right-handed woman. She had a left MCA infarct in 1997. Her spoken language is typical of Broca's aphasia. It consists mostly of single words combined into short 2–3 word phrases with no or little syntax. In addition, she has problems in comprehending

syntax, making a large number of reverse role errors in a sentence-picture matching task, but she is unimpaired on tests of semantics. She has a mild reading impairment, primarily involving non-words. She has a small hearing impairment (17 dB in left and right ears) which is well within the range for the controls. An MRI scan in 2000 revealed extensive damage to the L peri-sylvian region, extending into the left corpus striatum, with preservation of temporal cortex (Fig. 1).

4. AS is a 57-year-old right-handed woman. She had a MCA aneurysm in August 1998. Like CH, she makes many reverse role errors on a sentence-picture matching task, suggesting that she has problems with syntactic processing, while showing no evidence of a semantic impairment. In addition, she can repeat single words better than she can repeat sentences. In terms of her reading abilities, she has only a very mild reading impairment. Her spoken language is non-fluent and consists of short

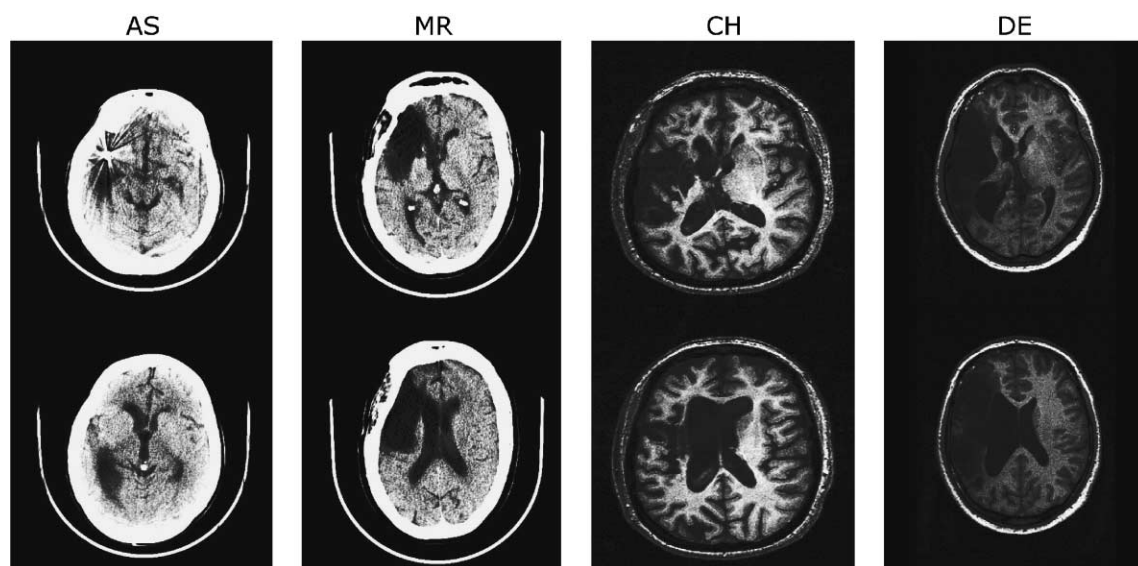


Fig. 1. Representative axial slices (CT for patients AS and MR and T1 weighted MRI for patients CH and DE) showing the inferior frontal and superior temporal damage in the four patients.

Table 2

Mean real word-form frequency (per million) for the experimental conditions and mean durations (ms) for real word stems/second words and matched non-words

Condition	Frequency of inflected/ first real word	Frequency of stem/ second real word	Real word duration (ms)	Non-word duration (ms)
Regular past tense: <i>called/call-dalled/dall</i>	24	35	532	542
Pseudo-regular: <i>bald/ball-nalled/nall</i>	30	40	506	511
Irregular past tense: <i>wrote/write-jote/jite</i>	18	31	555	577
Pseudo-irregular: <i>boat/bite-poat/pite</i>	27	28	537	545
Single feature different: <i>rope/robe-fope/fobe</i>	15	28	552	557
Additional phoneme: <i>claim/clay-vame/vay</i>	17	38	497	506

simple phrases. She has a moderate hearing impairment (18 dB in the left ear and 20 dB in the right ear) but this is well within the range of our control subjects. A CT scan taken in September 1998 showed a hypodensity in L superior temporal lobe and in Broca's area (Fig. 1).

### 3. Phonology and the past tense: JUDGEMENT STUDY

The question we address in the first part of this study is whether these four patients' difficulties in processing regular past tense forms can be understood in terms of the phonological properties of these forms alone. We therefore designed an experiment where the patients are asked to discriminate inflected forms (both regular and irregular), matched in their phonological properties to uninflected real words and non-words. If the patients' problems with regularly inflected forms are due to their particular phonological (rather than morphological) structure, then they should have problems with both the regularly inflected past tense forms and the matched uninflected forms. If, however, the patients have difficulty processing the regulars because of their morphological composition, then they should have significantly greater problems with the regular past tenses than with phonologically matched uninflected forms, whether real words or non-words.

#### 3.1. Method

##### 3.1.1. Design

We used a reaction time task in which subjects heard pairs of words or non-words (e.g. *played-play*, *played-played*, *thrayed/thray*, *thrayed/thrayed*) and pressed a response key if the two stimuli in a pair were different. The first word in a pair was spoken in a male voice while the second was spoken by a female. This was to ensure that the same-different judgement was not made on the basis of low-level acoustic differences between the words.

##### 3.1.2. Materials

The experiment consisted of sets of real words and non-words. For the real words, there were four test conditions and two control conditions. Of the four test conditions, two

consisted of pairs of morphologically complex words and their stems—one of regularly inflected forms (*played/play*, *pulled/pull*) and the other of irregularly inflected forms (*sank/sink*, *taught/teach*). The words in the two sets were paired with two sets of uninflected words (called "pseudo-regular" and "pseudo-irregular" forms), as far as possible on the basis of their phonological similarity (e.g. *grade/grey*, *port/peach*). Two further control conditions asked subjects to discriminate morphologically simple pairs differing either by a single feature (e.g. *bat/bad*), or by the removal of a single phoneme (e.g. *pike/pie*).

In addition, there were four non-word conditions, exactly matched phonologically to the real word conditions. There was a regular past tense non-word condition (*thrayed/thray*), matched to the regular and pseudo-regular conditions, an irregular past tense condition (*hort/heach*), matched to the irregular and pseudo-irregular conditions, a single feature difference condition (*gat/gad*) and a single phoneme condition (*snike/sny*.) There were the same number of words and non-words in the experiment (see Table 2 for details).

#### Real word test conditions

##### Regular past tense condition

We selected a set of 30 regularly inflected past tense words which were paired with their stems (e.g. *played-play*, *jumped-jump*). The past tenses were selected to have a range of offsets, so that they were representative of the type of consonant cluster that typically occurs when the past tense is used. We believed that this was essential for a proper test of the claim that difficulties with the regular past tense reflect the phonological complexity of regular past tense endings. For this reason, we included 12 pairs where the resulting consonant clusters either have no morphologically simple counterpart, as in the [vd] of *lived* or the [bd] of *grabbed*, or where suitable pseudo-regular pairs cannot be found, as in the [kt] of *picked*.<sup>1</sup> The remaining 18 regular past tense forms either ended with a simple [d] as in *paid* or *died*, or with clusters such as [ld] or [st] which have suitable

<sup>1</sup> Although there are monomorphemic forms such as *fact* that end with the sequence [kt], it is not possible to find a matching pseudo-stem—the form *fac* does not exist. Cases like *pack/pack* are ruled out because *pack* is homophonous with the past tense form *packed*.

monomorphemic counterparts—e.g. *pulled/pull* can be matched to *mild/mile*.

#### Pseudo-regular past tense condition

We chose 30 monomorphemic words ending either in a vowel + /d/, as in *slide* or *feed*, or in a consonant + /d/ or /t/, as in *fund*, *mild*, and *crest*. Word-pairs similar to the regular past tense-stem pairs were constructed by removing the final /d/ or /t/ to create an unrelated monomorphemic word, as in *crest/cress*, *slide/sly*, and *fund/fun*. The sets of regular and pseudo-regular items were matched overall on word-form frequency [1] and for types of consonant cluster at the onset of the words. As noted above, 12 of the regular past tense forms did not have exact pseudo-regular counterparts. The remaining 18 could be exactly matched in terms of the phonological properties of their final consonants, and in many cases in terms of their vowels as well (e.g. *paid/pay*, *raid/ray*).

#### Irregular past tense condition

We selected 30 irregularly inflected past tense pairs, such as *taught/teach* or *broke/break*. These items were matched with the regular past tenses on stem frequency and, as far as possible, on the frequency of the past tense form.

#### Pseudo-irregular past tense condition

30 pairs of monomorphemic words were chosen that matched the phonological properties of the irregular past tense items (*belt/bell*, *port/peach*). These pairs of words could almost all be fully matched to their corresponding irregular past tense/stem pairs (*spelt/spell*, *taught/teach*).

As with the regular conditions, the irregular and pseudo-regular conditions were matched for word-form frequency and complexity of word onset. The regular and irregular conditions were matched overall on frequency (see Table 2).

#### Real word control conditions

We included two real word control conditions to provide a measure of phonological processing independent of past tense morphology.

#### Single feature condition

This condition consisted of 20 pairs of words that differed from one another by a single phonetic feature (e.g. *seed/seat* contrasting in voice and *skim/skin* contrasting in place of articulation). This parallels the minimal pair distinctions that subjects are typically asked to make in tests of phonological function, except that here the tests are conducted under conditions requiring a speeded response.

#### Phoneme condition

20 pairs of words were selected that differed by a single additional phoneme (*claim/clay*, *plank/plan*) in the

same way as the pairs in the regular past tense conditions (*played/play*, *turned/turn*). However, in this condition, the additional phoneme—the final /m/ in *claim*, for example, or the final /k/ in *plank*—is not a potential grammatical morpheme in English. This condition was included to determine whether difficulties with the past tense forms could be attributed to a general inability to perceptually analyse the final consonant in a word, whether or not this was potentially decomposable into a separate grammatical morpheme.

#### Non-words

Half of the items in this experiment were non-words. These were included for two main reasons. First, if patients have a strictly phonological processing deficit which impacts on their ability to process regular past tense forms, then this should affect non-words as well as real words. Second, the high proportion of non-words should discourage the development of lexical strategies in which subjects used differences in word meanings to make same-different judgements.

We constructed four sets of non-words, matched to the phonological properties of the real words. Non-words were created by changing the initial consonant or consonant cluster of a real word, so that they were matched exactly to the real words in terms of the phonological properties of their vowel and their final consonant clusters. They were also well matched in average duration (see Table 2).

1. *Regular past tense non-words*: This was a set of 60 non-words, of which 30 were created from the real word regular past tense items and 30 from the pseudo-regular items, as in pairings like *hugged/hug*–*nugged/nug*. Thus, unlike the regular/pseudo-regular real word pairings, here every real word regular past tense pair had a non-word equivalent.
2. *Irregular past tense non-words*: The same procedure was followed for non-words that matched the phonology of the irregular real word items. There were 60 irregular non-word items, 30 representing the irregular real words and 30 the pseudo-regular real words.
3. *Feature*: The 20 pairs of non-words were created from the single feature real word condition.
4. *Phoneme*: The 20 pairs of non-words were created from the additional phoneme real word condition.

The complete set of items consisted of 160 pairs of real words and 160 pairs of matched non-words. Each pair of items was presented twice; once where the two words were different (e.g. *jumped/jump*, *chest/chess*, etc.) and once where they were the same (e.g. *jumped/jumped*, *chest/chest*). Items were pseudo-randomised to ensure that all conditions were spread equally across the whole experiment and to make sure that “same” and “different” pairings of each word-pair did not occur close together. The pseudo-randomisation also ensured that no long strings of non-words or real words were presented consecutively and that items from the same condition were not clustered together. The items in their final testing order were divided

into four separate experimental blocks. A set of 25 real word and non-word practice items was constructed for presentation at the beginning of the experiment. Five lead-in items were included at the beginning of each experimental block to allow time for the participants to settle into their task at the beginning of each testing session.

The items were recorded onto tape by a male and a female native speaker of British English. The stimuli were then transferred onto hard disk and sampled into individual speech files at a sampling rate of 22,050 kHz. The first item in a pair was presented in the male voice, and the second in the female voice.

### 3.1.3. Procedure

The experiment was run using DMDX experimental software package [3]. Participants were tested in quiet conditions in front of a response box and wearing headphones. At the beginning of each trial they heard the first stimulus in a pair spoken in the male voice. For both real words and non-words, the first word was always the past tense or its equivalent. After a 200 ms delay the second stimulus was presented in the female voice. There was then a further 1500 ms rest before the next stimulus pair was presented and a 3000 ms time-out.

Participants were asked to press a response button if the two items they heard sounded different, but to refrain from responding if they sounded the same. The importance of listening for differences in the sound of the items was emphasised.

The experiment began with a practice session and continued in four blocks of experimental trials with short breaks between each block. In all the experiment lasted about 50 min.

## 3.2. Subjects

In addition to the four non-fluent patients, we tested eight subjects from the CSL subject panel on the phonological judgement task. Their mean age was 66.8 years (range: 61–73 years) and mean hearing loss was 22 dB (range: 10–30 dB) for the left ear and 22 dB (range: 17–30 dB) for the right ear. These subjects were tested in the same quiet conditions as the patients.

## 3.3. Results

### 3.3.1. Patients: RT data

We only included correct responses (successful detection of a difference) in the RT analysis. Since data from patients can be particularly variable and unevenly distributed in the upper tail of the distribution, we applied an inverse transformation to the data in order to make it fit a more normal distribution, without the need for removing or replacing outliers [14]. To further reduce variability in the data, we only included items in each condition where the error rate was 25% or less across the four patients. The resulting harmonic

Table 3  
Non-fluent patients: harmonic mean RTs (ms) and error rates (%)<sup>a</sup>

Condition	Real words	Non-words
Regular		
RT	1420 (45)	1258 (29)
Error	30.8 (3.9)	21.7 (5.2)
Pseudo-regular		
RT	1252 (38)	1230 (40)
Error	25.0 (5.1)	22.3 (2.4)
Irregular		
RT	848 (30)	889 (38)
Error	2.5 (1.4)	2.5 (1.4)
Pseudo-irregular		
RT	836 (28)	831 (24)
Error	1.7 (1.2)	6.0 (2.4)
Feature		
RT	1151 (36)	1151 (37)
Error	15.0 (4.2)	25.0 (7.3)
Phoneme		
RT	1044 (31)	1074 (40)
Error	5.0 (3.1)	6.3 (3.1)

<sup>a</sup> Standard errors (the standard errors are derived from the retransformed item means) are shown in parentheses.

mean RTs (the retransformed means) for each condition are shown in Table 3 and Fig. 2. The mean RTs for the patients ranged from 816–1255 ms.

An ANOVA with two between items factors (word-type: real word or non-word, and condition: regular past, pseudo-regular, irregular past, pseudo-irregular, single feature and additional phoneme) was conducted on the item means. This showed no overall difference in reaction times to real words and non-words ( $F < 1$ , real word mean = 1019 ms, non-word mean = 1023 ms). Reaction times between conditions differed significantly ( $F(5, 269) = 75.12$ ,  $P < 0.001$ ), but there was no word-type by condition

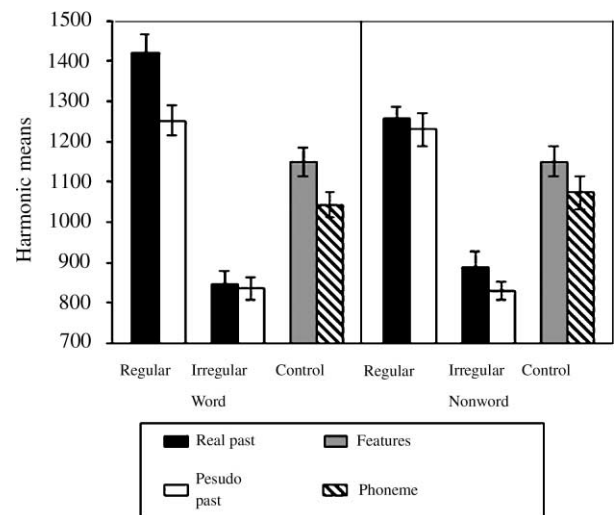


Fig. 2. Patients' RTs for words and non-words.

interaction ( $F(5, 269) = 1.23, P > 0.2$ ). To evaluate the effects for specific conditions in more detail, we also carried out separate one-way analyses for the real word results and for the non-word results.

Response times (and error rates) were greatly elevated for the regular and pseudo-regular conditions, both for real words and non-words, averaging 1290 ms for these four conditions. The effect was strongest for the regular real words, at 1420 ms, which were significantly slower than both the real word pseudo-regulars ( $t(41) = 3.12, P < 0.01$ ) and the non-word regulars ( $t(42) = 3.31, P < 0.025$ ). In a separate two-way analysis of variance, just on the regular and pseudo-regular real words and non-words, the interaction between word-type and regularity approached significance ( $F(1, 86) = 3.36, P = 0.07$ ).

The same general pattern was obtained when we examined the subset of the stimuli for which there was a complete phonological match between real regulars and pseudo-regulars (as noted above, 12 of the 30 real regulars did not have direct pseudo-regular counterparts). These were eight word-pairs where the regular pairs (e.g. *tried/try*) not only ended in the same consonants as the matched pseudo-regular pair, but also shared the same vowel (as in *pride/pry*). For these stimuli, the mean RT for the real regulars was 1514 ms, which was significantly slower than the mean of 1265 ms for the pseudo-regulars ( $t(7) = 2.95, P < 0.025$ ).<sup>2</sup> This is very similar to the pattern for the whole set, and is inconsistent with an account of the difference between real word regulars and pseudo-regulars in terms of the greater phonological complexity of the regulars.

Responses were fastest to the irregular and pseudo-irregular real words and non-words, averaging 851 ms across the four conditions, with no significant differences between them. These differences between the regular and irregular stimuli were highly significant for both the real words ( $t(101) = 13.42, P < 0.01$ ) and for the non-words ( $t(103) = 11.30, P < 0.01$ ). Looking at the two control conditions—single feature change and phoneme removal—response times were increased relative to the irregular sets, but were again significantly faster than to the regulars and pseudo-regulars. This held both for the real words (regular past tense versus single feature:  $t(37) = 5.01, P < 0.001$ , pseudo-regular past tense versus single feature:  $t(40) = 2.11, P < 0.05$ , regular past tense versus additional phoneme:  $t(38) = 6.89, P < 0.001$ , pseudo-regular past tense versus additional phoneme:  $t(41) = 4.37, P < 0.001$ ) and for the non-words ( $t(61) = 2.23, P < 0.05$  for single features and  $t(63) = 4.01, P < 0.001$  for the additional phoneme lists). The relatively large increase in RT for the single feature condition, and the high error rate, suggests that the patients were having difficulties with fine phonetic discrimination under the demanding conditions of this speeded task. They performed relatively well in the

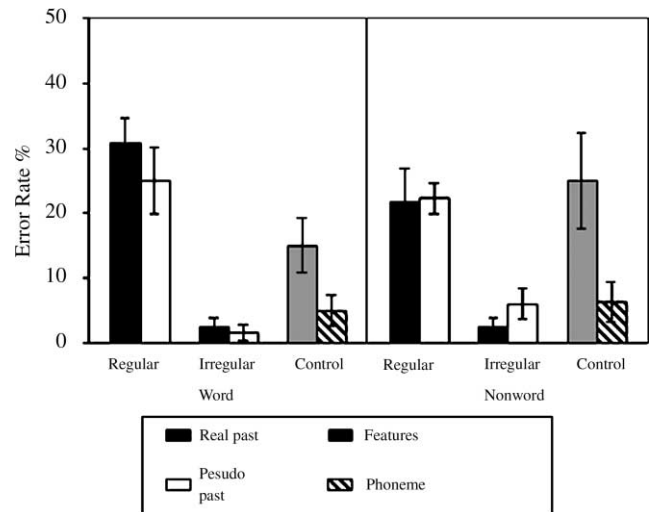


Fig. 3. Patients' errors for words and non-words.

additional phoneme condition, where responses were faster and error rates much lower.

### 3.3.2. Patients' errors

The error rates (failures to detect a difference) across conditions are given in Table 3 and plotted separately in Fig. 3. Consistent with the RT data, errors are greatly increased in the real word and non-word regular and pseudo-regular conditions, and also in the single feature control condition.

An overall between items ANOVA, with the factors word-type and condition show that there was no difference in error rates between words and non-words ( $F < 1$ ), but that there were differences between conditions ( $F(5, 307) = 17.61, P < 0.001$ ), with patients making more errors in the pseudo-regular, regular and single feature conditions compared to the other conditions. There was no word-type by condition interaction ( $F(5, 307) = 1.42, P > 0.2$ ). We also carried out separate one-way analyses on the real word and non-word data.

Error rates were uniformly high for the regular and pseudo-regular real word and non-word conditions (averaging 25%). Although the pattern across these four conditions is numerically similar to the RT results, with the highest error rates for the real word regulars, none of these differences is significant (real word regulars versus pseudo-regulars:  $t(58) = 0.91, P > 0.3$ , real word regulars versus non-word regulars:  $t(58) = 1.41, P > 0.1$ ). Error rates are much lower for the irregulars, averaging just 3.1% over the four real word and non-word irregular conditions. Again, this is a much larger difference than for the controls (see Table 4), where error rates were essentially identical for regulars (at 1.3%) and irregulars (at 0.7%)

Turning to the two control conditions, the error patterns also parallel the RT results, with high error rates for the single feature condition (averaging 20%) and much better performance on the additional phoneme condition (mean

<sup>2</sup> Similar issues do not arise for the non-word regular set, since these are all fully matched to their corresponding real word regulars.



Table 4  
Controls: harmonic mean RTs (ms) and error rates (%)<sup>a</sup>

Condition	Real words	Non-words
Regular		
RT	943 (18)	967 (20)
Error	0.4 (0.42)	2.1 (0.9)
Pseudo-regular		
RT	900 (27)	930 (25)
Error	1.3 (0.72)	1.3 (0.7)
Irregular		
RT	767 (20)	828 (18)
Error	0.0 (0)	1.3 (0.7)
Pseudo-irregular		
RT	797 (19)	801 (23)
Error	0.8 (0.84)	0.9 (0.6)
Feature		
RT	907 (26)	955 (32)
Error	0.6 (0.63)	4.4 (3.18)
Phoneme		
RT	865 (27)	908 (30)
Error	0.6 (0.63)	1.3 (0.86)

<sup>a</sup> Standard errors are shown in parentheses.

of 5.6%). For the real words, error rates were still significantly higher for the regular and pseudo-regular condition compared with the single feature condition (regular past tense versus single feature:  $t(48) = 2.68$ ,  $P = 0.01$ , pseudo-regular versus single feature:  $t(48) = 1.40$ ,  $P > 0.1$ ). For the non-words, where error rates were highest overall in the single feature condition, there is no difference between the regular past tense errors and the single feature errors (regular non-words versus single feature:  $t(48) = -0.38$ ,  $P > 0.7$ , pseudo-regular non-words versus single feature:  $t(48) = -0.33$ ,  $P > 0.7$ ).

### 3.3.3. Control subjects RT data

We analysed the control group data in the same way as the patient data. These results are shown in Table 4 and Fig. 4. The mean RTs for the controls ranged from 786 to 1157 ms.

Overall the controls perform rapidly and accurately, with relatively small differences between conditions. An ANOVA with two between item factors (word-type and condition) showed that reaction times to real words (855 ms) were faster than to non-words (890 ms) ( $F(1, 306) = 7.32$ ,  $P < 0.01$ ). This is a different pattern to the patients who showed no overall difference in RTs for real words and non-words. Consistent with the patient analyses, however, there were significant differences between conditions ( $F(5, 306) = 20.59$ ,  $P < 0.001$ ), which did not interact with word-type ( $F < 1$ ).

Separate one-way ANOVAs on real words and non-words confirmed, first, that there were significant differences between the different real word conditions ( $F(5, 154) = 11.73$ ,  $P < 0.001$ ). Response times were slowest for the

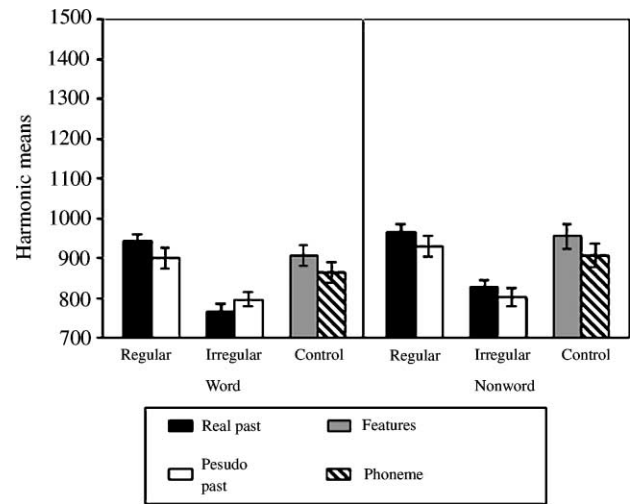


Fig. 4. Control subjects' RTs for words and non-words.

regular conditions (922 ms) and fastest for the irregulars (782 ms). However, there were no significant differences between either the real regulars and the pseudo-regulars ( $t(58) = 1.46$ ,  $P > 0.1$ ) or between the real irregulars and the pseudo-irregulars ( $t(58) = -1.17$ ,  $P > 0.2$ ), indicating that neither type of inflection presented any special problems to the control group. A similar pattern was found for the non-words, with slower responses to the regular conditions (948 ms) than to the irregular conditions (814 ms), but with no significant differences between regulars and pseudo-regulars ( $t(58) = 1.05$ ,  $P > 0.2$ ) or between irregulars and pseudo-irregulars ( $t(57) = 1.00$ ,  $P > 0.3$ ).

Turning to the control conditions, there was no difference between the additional phoneme condition and the real word pseudo-regulars ( $t(46) = -0.96$ ,  $P > 0.3$ ), but a significant 78 ms difference with the regular past tense ( $t(49) = -2.69$ ,  $P = 0.01$ ). For the non-words, neither of these contrasts were significant. RTs were slower for the real word single feature condition, with no differences in reaction times between either the regular past tense condition or the pseudo-regular condition and the single feature condition (regular versus single feature:  $t(49) = -1.24$ ,  $P > 0.2$ , pseudo-regular versus single feature:  $t(46) = 0.23$ ,  $P > 0.8$ ). A similar pattern held for the non-word sets, with no difference in RT between single feature and regular conditions.

### 3.3.4. Control subjects errors

The error rates, given in Table 4, are very low throughout. An ANOVA with two independent factors (word-type and condition) revealed a marginally significant effect of word-type with non-words (mean of 1.7%) producing slightly more errors than real words (mean of 0.6%,  $F(1, 305) = 3.00$ ;  $P < 0.09$ ). There was no difference in error rates between conditions and no interaction between condition and word-type (both  $F < 1$ ).

### 3.4. Discussion

The first part of this study is directed at the question of whether patients' apparently selective deficits in processing regular past tense forms can be accounted for solely in terms of the special phonological properties of these forms. For the unimpaired subjects, the control group, there is very little evidence, either from RT data or from error rates, that the characteristic phonology of the regular inflection poses any special difficulties in perceptual processing and discrimination. Although RTs are generally elevated relative to the irregular sets, they are also increased for the additional phoneme and single feature sets, where responses also have to be delayed until all of the second word of each word-pair has been heard, and where fine phonetic discriminations involving unvoiced stops are also often required. Responses to the irregulars are faster because the divergent phonetic information typically arrives much earlier in the word, at vowel onset.

The patient group shows a much more differentiated set of responses to the experimental conditions. Like the controls, they are fast and accurate in making same–different judgements to the class of irregular stimuli, whether real or pseudo-irregulars, and irrespective of lexical status. The overall patient mean RT (851 ms) and error rate (3.1%) is not substantially different from the corresponding values (782 ms, 0.7%) for the controls. Unlike the controls, however, the patients show considerably elevated RTs and high error rates for all of the stimulus sets involving the phonology of the regular past tense, whether real words or non-words. For the set as a whole, response times average 1290 ms, with error rates of 25%. The average difference here between the regular and irregular conditions, at nearly 450 ms, is so much larger than the corresponding difference (137 ms) for the control subjects that it is likely to reflect special processing problems, not just with the real regular past tense itself, but with any materials that share the phonological properties of these inflected forms—namely, ending with some allomorph of the [–d] affix, either following a vowel or in a consonant cluster. Note that performance is considerably better in the additional phoneme condition (mean RT of 1151 ms, error rate of 5.7%). This requires similar discriminations to the regular and pseudo-regular conditions, but here none of the final consonants are potential inflectional morphemes.

Even if we attribute this drop in performance on the regulars and pseudo-regulars solely to phonological factors, this is insufficient to account for the further important aspect of the results—that the patients' performance is worse still on the regular real words, where the RT of 1420 ms is significantly slower than in the other three conditions (averaging 1247 ms). For the comparison with the non-word regulars there is a complete phonological match with the real word regulars. For the pseudo-regulars, the effect holds both for the two sets as a whole, and also when the comparison is restricted to the pairs for which there is a complete

phonological match. This is clearly inconsistent with the claim that selective impairments in processing the regular past tense can simply be reduced to a general impairment in phonological processing, without reference to the morphological properties of the linguistic entities involved.

It still remains to be determined, however, why the patients showed such difficulties, across the board, with the real word and non-word regular comparisons. Can these difficulties be simply accounted for by the phonological or acoustic–phonetic difficulty of the judgements involved? To evaluate this, we need some assessment of the patients' baseline speech processing capacities. This is provided by the second component of this study.

## 4. Tests of phonological processing function

The second part of this study addresses the question of whether patients who have greater problems in processing the regular than the irregular past tense also have a generalised speech processing deficit, as apparently required by the Joanisse and Seidenberg [4] type of account. Our more neurologically differentiated approach allows for disruption of morpho-phonologically specific processes without an accompanying disruption to more basic speech processing functions. To address these issues, we tested the patients on a range of standard tests used to assess neuropsychological patients for phonological impairments, selecting tests from the PALPA [6], together with the Rosner test of auditory analysis skills [15]. Because of limitations of some of these tests, we also administered a newly developed in-house test of phonological segmentation (CSL segmentation test).

### 4.1. PALPA tests [6]

- (i) *Same–different discrimination using word minimal pairs: picture version.* Subjects hear pairs of monosyllabic words which differ in one phonetic feature. Differences occur in initial (*lip-nip*) or final positions (*bed-bet*). Subjects indicate their choice by pointing to relevant picture.
- (ii) *Same–different discrimination using word minimal pairs.* This is the same as test (i) except that the subject has to say whether the pairs are the same or different.
- (iii) *Same–different discrimination using non-word minimal pairs.* This is the same as test (iii) except that it involves non-words. Good discrimination of non-words suggests that low-level auditory processing is unimpaired.
- (iv) *Word rhyme judgements.* Subjects are asked whether two spoken words rhyme (e.g. *train-crane*). This is a more meta-linguistic task which also tests integrity of short-term phonological store.
- (v) *Phonological segmentation of initial sounds.* Subjects are presented with a set of monosyllabic words and non-words, all having a CVC structure, and asked to

identify the first sound in each item and point to the letter denoting that sound.

- (vi) *Phonological segmentation of final sounds*. This is the same as test (v) except that subjects have to identify the final sound.

#### 4.2. Rosner test of auditory analysis skills [15]

In this test, subjects are presented with single words and asked to repeat them after removing the first syllable or the first phoneme. The words are a mixture of nouns and verbs.

#### 4.3. CSL segmentation test

Because of the limitations of the Rosner test and some of the PALPA tests, we constructed a more extensive test to examine patients' abilities to segment phonemes in spoken words. Subjects heard a spoken word and were asked to repeat it, to ensure that they were able to produce the word. They were then asked to remove either the initial or final sound and repeat the remaining word. The to-be-segmented word (e.g. *scarf*) was chosen such that it always left a real word after the first phoneme (*calf*) had been removed and after the last phoneme (*scar*) had been removed. This was to ensure that any differences between the patients' abilities to segment the initial or final phoneme could not be attributed to the differences in the words used. It was also important because some of our non-fluent patients are also deep dyslexic (e.g. DE) and have difficulty repeating non-words. There were 42 words in the set. The items were divided into two lists. With the first list, the experimenter asked subjects to strip off the initial phoneme and repeat the resulting word. The second list consisted of the same words, in a different random order, for final phoneme segmentation.

#### 4.4. Results of tests of general phonological function

In all of these tests, unimpaired control subjects score almost at ceiling (see [6,15]). The patients' results are shown in Table 5, where we can see that they all did well on the three PALPA minimal pair discrimination tests of

acoustic–phonetic processing, with average scores ranging between 86 and 96% correct. Although this is slightly down on the levels of the control subjects, it is well above the chance level of 50% and suggests that none of the four patients had a significant impairment in the acoustic–phonetic analysis processes required to make fine phonemic discriminations in lexical and non-lexical contexts. It is hard to judge whether these minor impairments would count as phonological impairments in the context of connectionist models of the Joanisse and Seidenberg [4] type. In terms of our neurologically based model, we can speculate that preserved acoustic–phonetic analysis capacities reflect sparing of primary auditory inputs to Heschl's gyrus and surrounding superior temporal areas, either bilaterally or, for patients like DE, in the right hemisphere.

Most of the patients were much more impaired on the segmentation tests, especially on single phoneme segmentation. We can assume that this task draws upon a more complex form of phonological analysis, requiring the overt decomposition of phonological representations constructed on the basis of underlying acoustic–phonetic analyses. There was some variation in performance across the four segmentation tests, due to differences in materials and tasks. However, the outcome was broadly consistent, with three out of the four patients finding segmentation more difficult than the other phonological tests, and clearly performing very much worse than the controls. DE was the most consistently impaired, with an average of 34% correct across the four phoneme segmentation tests. CH and MR did somewhat better, at 53 and 46%, respectively. AS, however, was essentially normal, averaging 92% correct relative to the controls' score of 97%. Within a single mechanism model of the Joanisse and Seidenberg type, it needs to be explained how these contrasting deficits in one aspect of phonological processing can occur in the context of the relatively minor deficits revealed by tests of acoustic–phonetic processing. From the perspective of a more neurologically based account, selective disorders of phonological segmentation are attributable to selective deficits of frontal systems critical to this type of phonological analysis (e.g. [2,18,20]).

Table 5  
Non-fluent patients: tests of phonological processing: percent correct

	DE	CH	MR	AS	Norms
PALPA/same–different word minimal pairs: picture task	100	97	88	85	97.5
PALPA/same–different word minimal pairs	90	75	89	100	98
PALPA/same–different non-word minimal pairs	90	86	83	90	98
PALPA word rhyme judgements: auditory	80	84	100	100	No norms
PALPA segmentation of initial sounds: words	77	100	77	100	97
PALPA segmentation of final sounds: words	50	66	73	100	96
Rosner segmentation					
Syllable	100	100	0	100	96
Phoneme	0	20	0	80	96
CSL segmentation					
Initial phoneme	0	47	29	85	95
Final phoneme	41	33	51	92	99

The potential dissociability of phonological and acoustic phonetic processing capacities from impairments in processing regular inflected forms can be brought out most clearly by comparing the two non-fluent patients (DE and AS) who showed the most marked contrast in tests of phonological function. DE has a severe phonological deficit, but AS clearly does not. Nonetheless, in the priming studies reported earlier [18] and in the phonological judgement study reported here, both patients show a significant and selective impairment for the real word regular past tense. Again, this is hard to square with an account of these impairments simply in terms of a more basic phonological processing deficit.

## 5. General discussion

In the studies reported here we found that the aphasic patients showed a distinctive pattern of performance which differed from the controls in certain crucial respects. Most importantly for the current issues, the patients' responses to the regular real words were significantly slower than to any other condition. In particular, latencies to the real word regulars were significantly slower than both the regular non-words, which were matched on an item-by-item basis with the real words, and the pseudo-regulars. Moreover, we found the same pattern when we selected out a subset of regular real word-pairs for which there was a complete phonological match with the real pseudo-regulars; once again the regular real words were significantly slower.

The fact that the patients' latencies are only significantly slower on the regular real words compared to the pseudo-regulars and not for either the irregulars or the regular non-words sets suggests that making a phonological discrimination between a regular past tense and its stem is different from discriminating between words with very similar phonology but which are unrelated morphologically. This set of results is inconsistent with the single system claim that patients' problems with the regular past tense can be attributed solely to their greater phonological complexity.

Instead, we suggest that the slower latencies to the regulars are due to the fact that it is only these stimuli that involve morpho-phonological processes which enable the complex form to be parsed into its stem and affix. It is this specific process which the patients have difficulties with. The additional processing cost associated with the regulars cannot be accounted for simply in terms of their more complex phonological structure, or greater phonological similarity of the past tense form and its stem. Since the real regulars only differ in terms of the presence or absence of extractable morphological structure, this is left as the only convincing explanation for the difference in RTs. This interpretation of the data is further supported by the subset of the regulars which were matched on an item-by-item basis to the phonological properties of the pseudo-regulars. Patients were significantly slower to respond to the real regulars (e.g. *pay/paid*)

compared to the matched pseudo-regulars (*ray/raid*), demonstrating that it is not the phonological properties of the regulars that results in their observed processing difficulty.

This interpretation of the RT data is also supported by the finding that not all of the patients have a severe phonological processing deficit, even though they all have problems with the regular past tense. This is not predicted by the single mechanism account, which claims that a deficit for the regulars should be accompanied by a severe phonological deficit. When we consider the patients' performance on the various tests of phonological function reported above, we see that they vary in the degree of their impairment. Although all of the patients were relatively normal on tests of acoustic-phonetic analysis, they varied in the extent to which they had problems on tests of higher-level phonological processing. DE, for example, was clearly impaired on phonological segmentation tests whereas AS showed at most a very mild deficit and was within the normal range on almost all of these tests. Nevertheless, both patients show an impairment for the regulars in a priming study comparing regulars and irregulars [18] and in the present study show the same pattern of slower responses to the regulars compared to the pseudo-regulars, but only for the real words. These results support our claims that general phonological processes and processes of morpho-phonological analysis can dissociate. AS's pattern of results on past tense priming and phonological tests shows that it is possible to have intact phonological processing in the presence of impaired morpho-phonological function. This argues against single system models that make no distinction between different types of phonological process, which therefore could not predict dissociations between these processes, and which would predict, moreover, that AS should not have problems with the regular past tense.

Taken together, the data reported in this paper suggest that the processing of regular past tense forms engages phonological processes which are specific to those morphologically complex forms which are compositional in structure and are not engaged by monomorphemic words. Since all of these patients have extensive L frontal damage, we can infer that these processes are associated with L inferior frontal cortex, especially Broca's area and related structures. Damage to these regions impairs the morpho-phonological processes which are necessary to parse a regularly inflected word into its constituent morphemes. The results reported here are consistent with data from neuropsychological, psychological, developmental, and linguistic studies which suggest that the regular and irregular past tense implicate different aspects of the language system.

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