Rules, representations, and the English past tense

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The significance of the English past tense in current cognitive science is that it offers a clear contrast between a potentially rule-based system – the procedures for forming the regular past tense – and an unpredictable and idiosyncratic set of irregular forms. This contrast has become a focus for a wide-ranging debate about whether mental computation requires the use of symbols. Highly regular combinatorial phenomena, such as the regular past tense, are prime candidates for rule-based symbolic computation. Earlier research concentrated on the evidence for this during language acquisition, looking at how children learned the English regular and irregular verb systems. Over the last five years attention has shifted towards the properties of the adult system, and we review here some recent research into the neural correlates of the two types of procedure. The evidence suggests that there are divergences in the neural systems underlying the generation and perception of regular and irregular forms. Regular inflected forms seem to involve primarily combinatorial processes, while irregular forms appear to have a hybrid status, sharing their semantic properties with the regular forms but diverging in the phonological domain, where their form representations are stored as complete units. This indicates that the regular and irregular past tenses may not, after all, provide a clean contrast in the types of mental computation they implicate.

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A fundamental issue in the cognitive sciences is to determine the nature of mental computation. Over the last decade the focus of this debate has been the contrast between classical views of mental computation, seen as the rule-based manipulation of strings of symbols with a syntax, as opposed to more distributed systems, operating subsymbolically and without syntax. Despite the pervasive and crucial nature of this debate, it has nonetheless been hard to find specific domains where empirical evidence could be generated that might decide between these two broad classes of views. The English past tense, perhaps surprisingly, offers one of the few cases where this seems to be true. Protagonists on both sides of the debate generally agree that the mental representation of the regular and irregular past tense of the English verb is a crucial test case. In this brief essay, we begin by explaining why this should be so, and then go on to focus on the recent emphasis, in our own work as well as in the work of others, on the neural correlates of the cognitive systems supporting the English past tense, and on the resulting claims for the neurological as well as functional dissociability of these underlying systems in the brain.

The English verb

The significance of the English verb is that its procedures for forming the past tense offer an unusually sharp contrast, within the same cognitive domain, between a highly regular procedure and a highly irregular and idiosyncratic set of exceptions. The great majority of English verbs, numbering 10,000 or more, form their past tense by adding the regular [-d] affix to an otherwise unchanged stem. Depending on the final segment of the stem, this affix is realized as /d/, /t/ or /ed/, as in verbs like *jump/jumped*, *agree/agreed*, *state/stated*. This is an apparently paradigmatic example of a rule-based process, applying across the board to almost all the verbs in the language, and which functions as the default procedure for all new verb formations. The only exceptions are about 160 English verbs, many of them among the most common words in the language, which have irregular past tense forms, and which do not employ the regular affixing procedure. These are verbs like *give/gave*, *tell/told* and *buy/bought*, where the past tense form is idiosyncratic and phonologically unpredictable.

Because of these unpredictabilities, it is unlikely that the acquisition of irregular forms involves the acquisition of rules of any sort, and it is widely agreed that they are learned and stored by some form of pattern-association process. The key theoretical issue, instead, is how to characterize the mechanisms underlying the regular past tense, and whether, in particular, the explanation of this classically

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rule-like procedure requires the postulation of an internal symbolic rule.

During the 'cognitive revolution' of the 1960s, the acquisition profile for the English past tense played an important role in establishing the view of mental computation as rule-based manipulation of symbol systems[1]. Children learning English seemed to move from an early stage of rote-learning of individual past tense forms to the induction of rule-based representations, as reflected in over-regularizations such as *goed* and *bringed*[2–4]. These followed an initial period when *went* and *brought* were used appropriately, and *goed* and *bringed* did not occur. It was argued that these anomalous forms could not be explained in terms of non-cognitive accounts of the acquisition process – for example, through some form of imitation, or through Skinnerian reinforcement procedures – because the child would never be exposed to these forms in the environment[5,6]. Their occurrence seemed to implicate strongly the child's induction of a linguistic rule – in this case, governing the formation of the regular past tense – with the subsequent misapplication of this rule to verbs which had irregular past tenses, and where, crucially, the child had previously used these irregular and highly frequent forms correctly.

This familiar and widely accepted argument from acquisition was fatally undermined by Rumelhart and McClelland's well-known demonstration that a simple two-layer connectionist network could apparently simulate the crucial characteristics of the learning sequence attributed to human learners[7]. In particular, this network moved from an early period of correct generation of irregular past tense forms to a phase of over-regularization, where these irregular forms were regularized in ways analogous to the child's errors. The network could not possibly be said to have learnt a symbolically stated rule. The fact that it could, nonetheless, exhibit apparently rule-governed behaviour, including apparent over-extension of these 'rules', has proved enormously influential in subsequent attempts to argue for (or against) a view of mental computation as rule-based and symbolic. Not surprisingly, it has also triggered an extensive and forceful debate.

Without discussing in detail the contents of this debate, it is fair to say that the controversy between connectionist and symbolic accounts of the acquisition process for the English past tense has effectively reached stalemate as far as the observable properties of the process are concerned. Early criticisms[8] of the Rumelhart and McClelland model did pinpoint important flaws in this specific model, but subsequent work – for example by Plunkett and Marchman[9] – has gone a long way towards meeting these criticisms (for a dissenting view, see Marcus[10]). Arguably, both connectionist learning models and accounts in terms of symbolic mechanisms each seem able to explain the qualitative and quantitative properties of the acquisition of the past tense by the human child.

To distinguish the two types of account it is necessary to look, in addition, at other aspects of the mental representation of English regular and irregular past tenses. Attention has shifted, accordingly, to the properties of the 'end state' – the manner in which regular and irregular forms are mentally represented by the adult native speaker of English. Current views of this, most prominently through the influence of Steven Pinker and his colleagues, have crystallized into the contrast between a single-mechanism approach, arguing for a complete account of mental computation in terms of current multi-layer connectionist networks, and a dual-mechanism approach, arguing that while connectionist accounts may be appropriate for the learning and representation of the irregular forms, a symbolic, rule-based system is required to explain the properties of the regular past tense, and, by extension, the properties of language and cognition in general[11]. Again, however, it is fair to say that current behavioural research, using the techniques of experimental cognitive psychology to probe the properties of these types of representation, has not come to a clear resolution. Evidence that regular and irregular past tenses behave differently, for example, in some priming tasks[12], is not necessarily inconsistent with connectionist learning models of the underlying representations[13].

Potentially more decisive evidence comes from examining the properties of the neural systems that underlie adult processing and representation of these two types of linguistic material. This can be done either by using imaging techniques to study patterns of neural activity in the intact system, or by neuropsychological research examining the effects of damage to these systems through injury to the brain. We describe below some recent neuropsychological work of our own, and then relate this to other neuropsychological work and to research looking at brain activity in the intact system.

Neuropsychological dissociations

The logic of the neuropsychological approach is relatively straightforward[14]. If regular and irregular forms are mentally represented and processed in fundamentally the same way, then both should be affected in similar ways by damage to the brain that disrupts morphological processing systems, and should show equivalent deficits in the appropriate experimental tests. But if there are two separate underlying systems, engaged, respectively, by the regular and irregular morphology, then it should be possible to find dissociations in performance between these two morphological domains.

To probe these possibilities we initially tested two aphasic patients (JG and DE) with well-documented difficulties in the comprehension and production of inflected forms in English. Both patients had typical 'agrammatic' speech, which is hesitant and rarely contains inflected words. In tests of their ability to interpret inflected words, they were able to access the stems of such words, but had consistent difficulties in interpreting the combination of the stem with an inflectional affix – as, for example, in forms like *jumps* or *smiling* (decomposable, respectively, into {jump} + {-s} and {smile} + {-ing}). We expected them to also have problems in the access and interpretation of regular past tense forms like *jumped* or *smiled*, which again involve the combination of a stem with a regular inflectional affix. The crucial question, however, was whether they would show the same kinds of problems for irregular forms like *gave* or *taught*, where the morphological relation between stem and past tense does not involve the same type of combinatorial operation. These irregular forms do not have

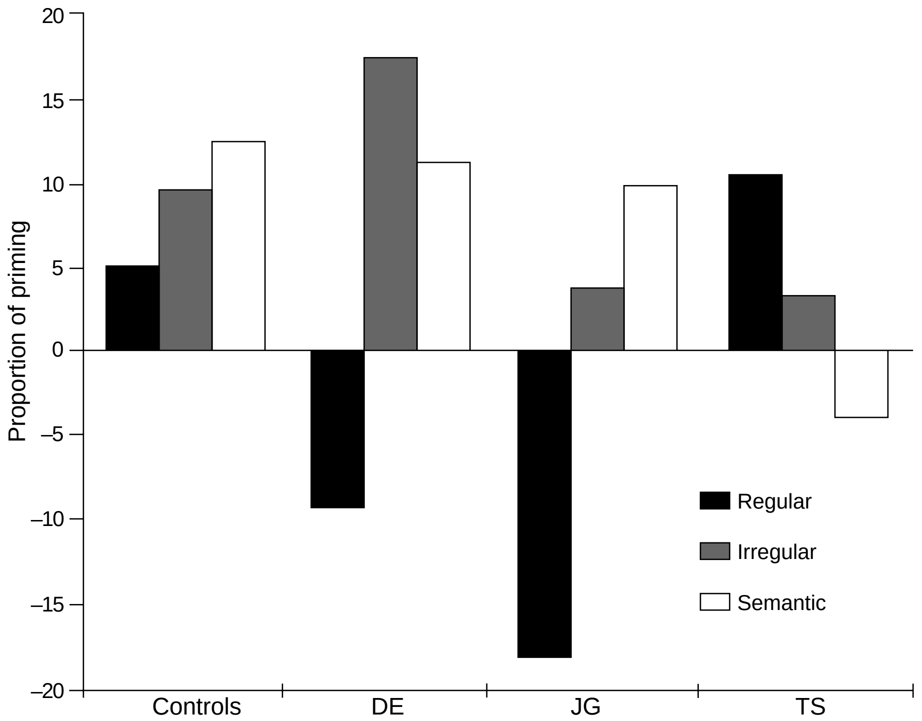

Fig. 1 Repetition priming. Effects across patients (DE, JG, TS) and control subjects for regular and irregular past tense primes and for semantic primes. Priming effects are expressed as response proportions (mean priming effect for each condition as a proportion of mean control RT for that condition) to normalize for differences in base reaction-time between subjects. (Modified, with permission, from Ref. 15.)

any internal morphological structure, and must be accessed as whole forms.

In order to bypass many of the problems inherent in testing the language abilities of such patients (e.g. reading difficulties and production problems) we focused on tasks involving the comprehension of spoken words. The patients were tested in a priming task, where a spoken target word is immediately preceded by a spoken prime word, and where the listener makes a timed lexical-decision response to the target stimulus ('Is this a word or not?'). For unimpaired listeners, responses to a target word are speeded up when it is preceded by a morphologically related prime word (as in the prime/target sequence *jumped/jump*) or by a semantically related prime (as in *swan/goose*), but not when the relationship is purely phonological (as in *gravy/grave*). Earlier studies confirmed that the patients could perform this task and that they showed normal levels of semantic priming – that is, they responded faster to a word like *goose* when it was preceded by a semantically related prime, such as *swan*, than by an unrelated word.

The results were clear-cut[15]. The control subjects, consistent with results for other groups of unimpaired adults in spoken priming tasks, showed significant priming for both regular and irregular past tense forms, with no interaction between regularity and priming. The aphasic patients (JG and DE), in contrast, exhibited a striking dissociation between regular and irregular morphology. They showed positive priming effects only for the irregular past tense, and not for the regular past tense. At the same time, like the controls, they showed significant priming for the semantically related pairs. This suggests a closer relationship between the processing of semantic primes and irregular past tense primes than between semantic and regular primes.

This relationship was sustained in testing of a third patient (TS), also classified as 'agrammatic', but with some right- as well as left-hemisphere damage. TS produces the opposite pattern to that shown by DE and JG, with normal performance on the regular past tense and no priming for the irregular past tense, accompanied by a failure of semantic priming. This double dissociation for the regular and irregular morphology is plotted in Fig. 1, together with the pattern of semantic priming effects.

The pattern of results across the three aphasic patients, showing a close relationship between priming for semantically related words and for irregularly inflected words, is supported by data from a very different kind of patient, the semantic dementia patient ES, who has a severe and progressive semantic impairment[16]. This patient's semantic deficit is demonstrated by her poor performance on tasks such as picture naming, defining words, word–picture matching, and property verification. When tested on the same priming experiment as the aphasics, she showed significant priming for the regularly inflected words but not for the semantically related words and the irregularly inflected pairs.

This overall pattern of results for the four patients has significant implications for the functional and neural architectures underlying the representation and processing of regular and irregular past tense forms in English. We now explore these.

Neural architecture

The most salient feature of the above results is the neurological dissociation of the regular and irregular past tenses, with the appropriate on-line tasks showing deficits in the access of regular but not irregular inflected forms for DE and JG, and the converse effect for TS and ES. These dissociations, together with the dissociations observed in other patient populations[17], allow us to develop more specific hypotheses about the different brain regions that underlie the representation and processing of the different types of past tense. It is generally assumed that left posterior frontal cortex (Broca's area) is involved in the processing of grammatical information. Damage to this area often goes hand-in-hand with syntactic impairments and problems with inflectional morphology. The neuropathological data from the two agrammatic patients, DE and JG, are consistent with this picture, as both have extensive damage to Broca's area. JG had a large perisylvian lesion involving most of the region supplied by the left (L) middle cerebral artery, including the L temporo-parietal cortex and L inferior and middle frontal cortices[18]. DE also had extensive damage in the L fronto-parietal-occipital regions (see Fig. 2). In both patients, there

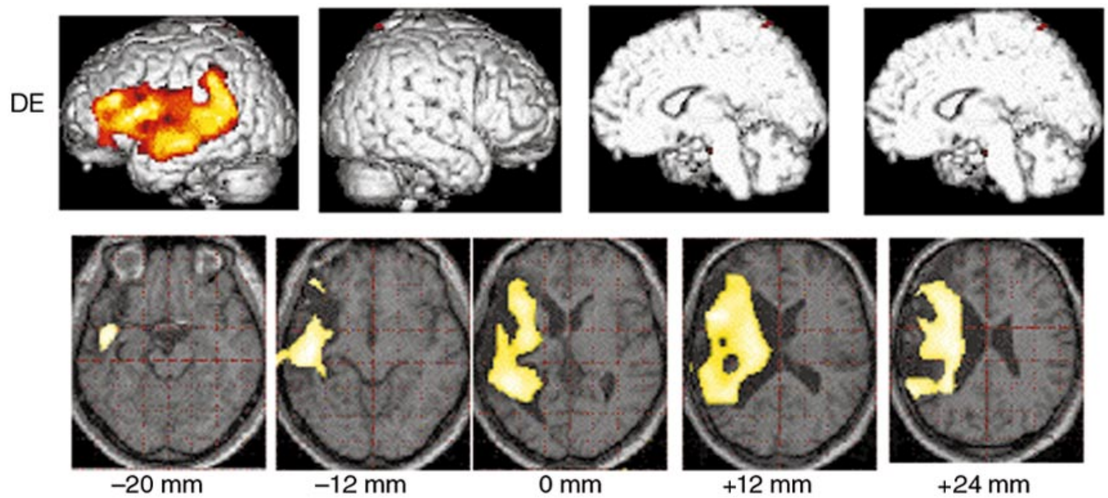

Fig. 2 Extent of DE's left hemisphere lesion. Using the technique of voxel-based morphometry[40], it is possible to reconstruct from a structural MRI scan the 3D volume corresponding to the areas of DE's brain damaged by his middle cerebral artery stroke. These areas are plotted in colour in the figure. The upper four images, from left to right, show the damaged areas rendered onto the surfaces of the left and right hemispheres, followed by two medial sections, oriented to left and right. The bottom five images are transverse sections through DE's brain, showing the lateral extent of the missing or damaged tissue at five different levels (using Talairach co-ordinates). Note the extensive frontal and temporal damage, but with sparing of inferior temporal cortex and no sign of any right hemisphere involvement.

was extensive L posterior frontal damage (Broca's area) while ventral temporal cortex was relatively spared.

Although TS showed some linguistic deficits that are typical of agrammatism – slow, hesitant speech and comprehension problems – he also had a relatively severe semantic deficit, which is atypical in agrammatism. Moreover, TS's neuropathology differed from that of JG and DE in that he had a large right-hemisphere (RH) lesion resulting from a middle cerebral artery stroke in 1995. A CT scan in October 1996 revealed RH inferior parietal and temporal damage and changes to the frontal and occipital lobes, as well as patchy ischaemic damage in left frontal, parietal and temporal areas. Thus, TS may have sustained mild damage to left-hemisphere (LH) posterior frontal cortex but, in addition, he clearly has bilateral temporal lobe damage as well. The temporal lobes are typically involved in tasks involving semantics[19] and damage to the temporal lobes has been associated with semantic deficits in cases of semantic dementia[20,21] and category-specific deficits for living things[22]. The fact that TS has damage to the temporal lobes may account for both his semantic deficit and for the lack of priming for irregularly inflected words. This analysis is supported by our fourth patient, ES, who is severely semantically impaired and who also shows no priming for the irregularly inflected pairs. She has substantial damage to the inferior temporal lobes, more extensive on the right, as determined by voxel-based morphometry of her MRI scan (courtesy of Dr Cathy Price; see Fig. 3). Broca's area was essentially intact, with

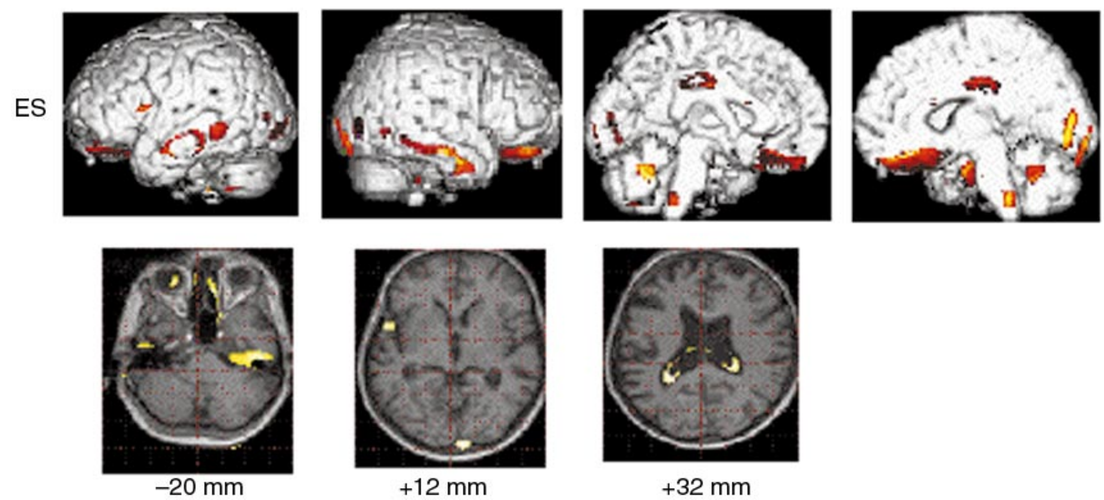

Fig. 3 Voxel-based morphometry for ES. Subsequent to a structural MRI scan, voxel-based morphometry was used to determine the damaged areas in ES's brain, caused by progressive brain disease. These areas are plotted in colour. Although there is wide-spread minor damage, the principal lesions are in the inferior temporal lobes. The upper four figures show the rendered surfaces of the left and right hemispheres, followed by medial sections oriented to left and right. Damage is clearly most advanced in the inferior surface of the right temporal lobes. As with DE (see Fig. 2), a number of transverse sections are also included, showing the extent of the lesions at three levels.

Table 1. Experimental contrasts for delayed repetition experiment

	Prime–Target relationship		
	Regular	Irregular	Semantic
Prime	called	gave	white
Target	call	give	black

only a tiny region (too small to be detected by radiological examination) identified by voxel-based morphometry as being damaged. Thus, both TS and ES had relatively extensive temporal lobe damage accompanied by mild damage in Broca's region, and both showed the same behavioural pattern of a semantic deficit going hand-in-hand with problems with the irregular past tense and with normal priming of the regular past tense.

The relationship between the patient data and their neuropathology provides evidence for the role of posterior frontal brain regions in the processing of the regular past tense and of the left ventral temporal lobe in the processing of the irregular past tense. These claims are supported by a recent neuroimaging study by Jaeger *et al.*[23] using PET, in which unimpaired adults were asked to produce either regular or irregular past tense forms. Jaeger *et al.* found increased activation in the left prefrontal cortex only during the production of regular past tense forms, and more activation in temporal and temporo-parietal regions only during the production of irregular past tenses. Although the interpretation of this study has to be qualified by doubts about uncontrolled differences in the difficulty of producing irregular and regular forms, the neuroimaging data and the patient neuropathology nonetheless present a consistent picture of the irregular and regular past tense being associated with different neural structures.

Functional architecture

Turning to the underlying functional architecture, the results for these patients suggest that the two morphological categories ally themselves with different domains of mental computation. DE and JG's deficits for the regular past tense are consistent with earlier evidence that these patients have marked deficits in combinatorial operations involving morphologically complex words – though note that recent evidence from our laboratory suggests that this deficit is restricted to the inflectional morphology; processes involving derivational morphology seem to be intact[24]. The irregular past tenses, in contrast, which are relatively spared for DE and JG, seem to accord with the evidence that these patients are relatively intact in their ability to access the semantic properties of morphologically simple words[25,26]. TS and ES, in contrast, who show no semantic priming, also show no sparing of the irregular past tense relative to the normal levels of priming they achieve for the regular past tense.

What are the functional implications of this neuropsychological association between intact semantic priming and intact irregular priming? What does it have to say about possible differences in the mental representation of regular and irregular forms, and how does this bear on the claims about types of mental computation that have motivated much of the interest in this research? We will consider two possible accounts, each of which corresponds to a 'dual mechanism' account in the broad sense that (1) different neural structures seem to be involved for regular and irregular past tense forms, and (2) that the way in which aspects of these forms are mentally represented seems to be qualitatively distinct. The first of these accounts explores the possibility that the priming relation between irregular past tense forms and their stems is primarily a semantic relationship, which parallels the priming relation between semantically related but morphologically unrelated words, such as *swan* and *goose*. For pairs like this, semantic priming reflects the spread or overlap of activation between two distinct lexical elements each with their own semantic representation. The possibility raised by the results here is that this also holds true for irregular past tense forms and their stems, so that *brought* and *bring*, for example, would be represented underlyingly as if they were two different words, with distinct semantic representations.

This would be a fundamentally different view of the relationship between an inflected form and its stem than is generally assumed to hold for the regular inflectional morphology. Here it is assumed that inflectional variants like *jump*, *jumped*, *jumps*, etc., do not correspond to separately represented underlying lexical elements, each with its own semantic representation. Rather, there is a single underlying representation, of the morpheme {jump}, capturing its abstract semantic, syntactic, and phonological properties. This morpheme has a number of inflectional variants, expressed phonologically as the stem plus an inflectional affix, but these are not separately represented in the mental lexicon. Priming effects, for these morphologically related words, are the consequence of repeated activation of the same underlying morpheme, and are not the result of spreading activation between distinct representations, as we established in earlier research looking at the basis for morphological priming in English[27].

This semantic account, based on the properties of the damaged system, seems inconsistent, however, with research we have been recently conducting into the properties of the intact system. One piece of evidence comes from a study using delayed repetition priming, where young adults make lexical decisions to spoken words presented one at a time, at intervals of two or three seconds, and where several words may intervene between the prime word and its related target. Note the contrast with the immediate repetition task used in the research with patients, where primes and targets are presented in pairs, and the gap between them is of the order of 250 ms. The reason for using the delayed repetition task here is that semantic priming drops away sharply over time but morphological priming does not. If the relationship between irregular past tense forms and their stems is more like the relationship between two separate but related lexical representations, then irregulars should pattern with the semantically related pairs, rather than with regularly related inflected pairs (see Table 1).

In our experiment the materials were presented with 12 items intervening between prime and target (approximately

35 seconds), and the outcome was unequivocal (see Fig. 4). There is no semantic priming at all at these long delays, but equally strong and significant priming for both regular and irregular primes. This is strong evidence that the underlying relationship between past tense form and stem is a morphological one in both cases, involving repeated access to the same underlying lexical element – in the case of these stimuli, the morpheme corresponding to the verb stem.

This alignment of the irregulars with regulars rather than with semantically related pairs is confirmed by a further study looking at the electrophysiological correlates of priming. Unimpaired young adults carried out cross-modal priming tasks, where an auditory prime is immediately followed by a visual target, while event-related scalp potentials (ERPs) were measured using a high-density 128-channel system. The subjects were tested with the same contrasts as in Table 1, covering regular and irregular pairs and semantically related pairs. Figure 5 plots the interpolated difference waves for the three critical conditions, showing the differences in responses to primed as opposed to unprimed targets. All three priming conditions have in common a central positivity, peaking in a time-frame of 340–400 ms after the onset of the visual target. This is the N400 effect standardly observed in semantic priming[28], as well as many other processing situations[29]. Both regular and irregular, however, diverge from the semantic case, in that in addition they each show significant left anterior negativities, typically associated with linguistic processing[30]. Thus, although there may be differences in detail in the pattern of activation for targets primed by regular as opposed to irregular primes, it is nonetheless the case that the irregulars globally parallel the regulars rather than the semantic pairs.

The outcome of these two studies indicates that the underlying relationship between an irregular past tense and its stem is more like the morphological relationship between a regular inflected form and its stem than it is like the relationship between pairs that are just semantically related. This, in turn, means that we cannot explain the neuropsychological results simply in terms of the semantic account sketched earlier, where the joint sparing of semantic priming and irregular priming is attributed to underlying parallels in their representational relationships. We are left, instead, with a view where the irregular form, like the regular form, maps onto the same underlying morpheme, and that it is repeated activation of this morpheme which gives rise to priming effects.

To explain why regular and irregular forms do, nonetheless, dissociate under some circumstances, we need to focus on the differences in the phonological representations of these forms. As noted earlier, we assume that regular inflectional forms are not stored as such, but are generated as required, as combinations of stems and inflectional affixes (*jump* + *s*, *jump* + *ed*, etc.). The recognition of these forms, where the underlying morpheme is activated by the incoming speech stream, requires a converse process of phonological parsing, where the spoken input is disassembled into stem and affix. This representational claim can be contrasted with those for monomorphemic forms, like *speed*, *elbow*, *table*, and so on. Here we assume that production and recognition involves the access of a stored full form, so that no process of phonological parsing is required in order to access this representation. The crucial claim here is that irregular inflected forms are also stored as full-form representations, with no internal phonological structure as combinations of stems and affixes. Again, access to these representations does not require them to be phonologically parsed.

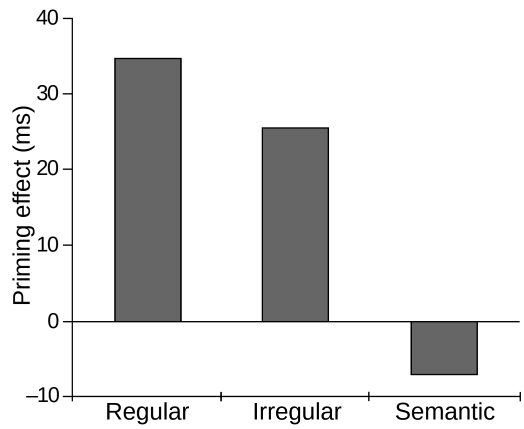

Fig. 4 Delayed repetition priming. Listeners made lexical decisions to primed and unprimed targets, and the difference (in ms) is plotted for each condition. No priming was found at these long lags for purely semantically related targets, but significant and equally strong priming was found for targets preceded by both regular and irregular morphologically related primes.

This points to an alternative explanation of why irregular primes pattern with semantic primes for the patient populations, and why these can remain intact when regular priming is disrupted. One of the defining features of agrammatic patients like JG and DE is that they have problems with processes of phonological assembly, especially where this involves the domain of 'morphosyntax' – that is, where words combine with syntactic elements, such as tense markers and plurals, to form inflectionally complex words. The spoken output of these patients is markedly lacking in regular inflected forms, and there is little doubt that they have comparable problems on the input side, in the phonological disassembly, or parsing, of inflected complex forms. This would lead to on-line impairments in the processing of regularly inflected words (such as the regular past tense), hence making these less effective as

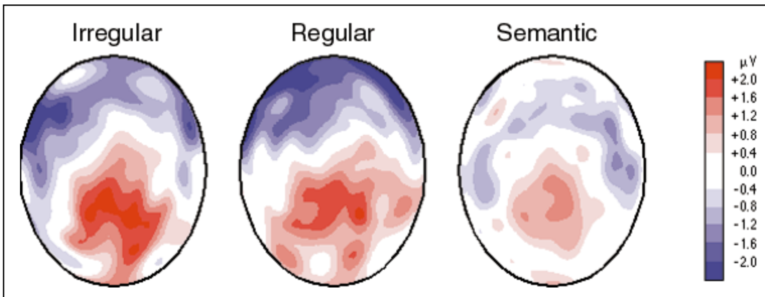

Fig. 5 ERP responses to primed targets. The interpolated difference waves are shown for each condition, computed by measuring the difference in electrical activity in scalp responses, over 128 electrode sites, when subjects were responding to primed as opposed to unprimed visual targets. Activity is summed here over the period 340–400 ms after the onset of the target. The targets were preceded either by unrelated spoken control words, or by semantically or morphologically related primes (see Table 1). This study was carried out at the MRC Cognitive Development Unit, in collaboration with Gergely Csibra, Harry Hatzikis and Mark Johnson.

Outstanding questions

- It is likely that the contrast in English between regular and irregular past tenses is cross-linguistically unusual, and provides an inadequate basis for claims about the universal properties of cognitive computation. A start has been made at looking into these questions in other languages, suggesting that there are interesting cross-linguistic variations – for example, between English, German[36] and Italian[37]. These are issues that need to be pursued across a wider range of language types.
- We raised the possibility that access routes via full-form representations and those that require phonological parsing are qualitatively distinct and neurologically dissociable. Are there other types of patient data that bear on this, and what differences might we predict in behavioural tasks?
- There is some evidence that patients who have difficulties with inflectional morphology have relatively spared derivational morphology. Does this relate to differences in the phonological aspects of these two types of morphology, or does it suggest a dissociation between different types of lexical combinatorial process?
- The work we report here is with isolated words. Would similar patterns of impaired and preserved performance emerge if we looked at processing of regular and irregular forms in more natural utterance contexts?
- Irregular past tenses in English are phonologically unpredictable, in the sense that the language learner cannot predict, given a stem, whether or not it has an irregular past tense, and, if it is irregular, what form it might take. This has to be learnt, on a case-by-case basis, for every irregular verb in the language. Nonetheless, there are subsets of irregular verbs that share phonological properties – for example, the verbs showing the *ing-ung* variation (as in *fling/flung*, *ring/rung*, *sing/sung*, etc.). These phonological sub-regularities play a role in generalization to new stems[38], and may well have influenced the historical evolution of the English system to its current state[39]. On the appropriate tests, would these more 'regular' irregular verbs behave like regular verbs in terms of their representation and access?

primes in the auditory–auditory immediate priming task. But for inputs that do not require this kind of phonological disassembly, including both monomorphemic words and irregular past tenses, there would be no on-line impairment, allowing prime words of this type to contact their underlying representations with normal efficiency and rapidity, so that subsequent priming, whether based on semantic overlap or on repeated access to the same morpheme, can also proceed normally.

What is less straightforward for this account is to explain why regular inflected forms can remain effective as primes when semantic priming and priming from irregular past tense forms is disrupted. If failure of semantic priming is due to underlying disruptions in storage of left infero-temporal semantic representations, and this also disrupts priming from irregular past tenses, then priming from regular past tenses should also be disrupted, given the argument we have just made for the underlying similarities in the way regular and irregular inflected forms connect to their stems. A phonological account would have to argue, instead, that the access routes via full-form representations and those that require phonological disassembly are qualitatively distinct and neurologically dissociable. Thus, when the full-form route is disrupted, reducing the effectiveness of both monomorphemic and irregular past tense primes, the listener is still able to access underlying lexical representations via intact fronto-temporal systems supporting phonological parsing and morphosyntactic analysis. Additional research is needed, however, to evaluate these speculations.

Dissociating types of mental computation?

The neuropsychological data from a variety of sources indicate that it is possible to dissociate at least some aspects of the neural systems supporting the perception and generation of regular as opposed to irregular past tense forms. This seems to follow directly from the predictions of a dual mechanism approach, and presents at least apparent difficulties for a single mechanism approach. However, the fact of dissociation itself is insufficiently constraining to discriminate among these approaches – there are, for example, developmental connectionist accounts which allow for the possibility that different cortical areas can recruit to themselves different aspects of the same processing domain, depending on the kinds of computational resources they require[31,32]. Learning the regular rule may differ from learning irregular exceptions in just this kind of way.

Additional constraints come from a functional analysis of how the facts of association and dissociation, in both the damaged and the intact system, point to more specific hypotheses about the underlying differences in the representation and processing of regular and irregular forms. We looked at two accounts, one semantic and one phonological, both of which had in common the assumption that regulars and irregulars differ along the dimension of what linguists would call 'listedness'[33] – that is, whether the underlying representation is stored as a whole unit, or whether it is generated, in a combinatorial manner, when required.

In the semantic domain, we evaluated the possibility that irregular past tense forms were separate lexical entries, rather than being linked to a verb stem in the same way as the regular forms, where these are assumed not to have separate representations. Alternatively, in the phonological domain, we considered the possibility that it is the form representation of the irregular that is stored as a separate entity, again contrasting with the regular inflected forms, which are assumed not be stored in the same manner. Neither account seems completely satisfactory on its own, and it is likely that they are complementary rather than mutually exclusive – especially given the special developmental history of the English irregular past tense[34,35]. Children initially learn forms like *took* and *brought* as forms in their own right, and analyse them as separate verb roots. It is only later, in a process that can take several years to complete, that they fully re-analyse *took* as part of the verb *take*, *brought* as part of the verb *bring*, and so on. These processes of analysis and reanalysis may give the irregular past tense its apparent hybrid status in the adult representational system, with listed phonological forms, but with their semantic and syntactic properties subsumed under those of the verb stems to which they are linked.

These arguments suggest an 'end state' with complex functional and neurological properties. The regular inflected forms do not have an independent representational status but are generated and parsed as required, depending on neural systems with a primarily LH frontal distribution. An important function of these systems is to support the processes of phonological assembly and disassembly which subserve the crucial domain of morphosyntax, where inflectional morphemes knit together strings of lexical morphemes into higher-order phrasal and clausal structures. Irregular past tense forms must also link into this domain, ultimately serving the same grammatical and interpretative functions as their regular counterparts. They seem to do so, however, through the involvement of somewhat different functional and neural subsystems, reflecting the listedness of their phonological representations, where there is no requirement to invoke combinatorial processes of phonological assembly. These subsystems seem to overlap substantially with those involved in the access and representation of morphologically simple forms, implicating the inferior temporal lobes in particular.

Within this framework, it is doubtful that an all-or-none computational dissociation between single and dual mechanisms will be a plausible outcome. It is becoming clear, both functionally and neurologically, that at least two, if not more, separable systems are involved. But any account of the computational properties of these systems, and any decision about the possible contrasts between them, is going to have to be firmly rooted, unlike most current models, in specific and testable proposals about the functional and neural architectures of the relevant cognitive and linguistic domains.

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