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Past tense in the brain's time: Neurophysiological evidence for dual-route processing of past-tense verbs

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ABSTRACT

A controversial issue in neuro- and psycholinguistics is whether regular past-tense forms of verbs are stored lexically or generated productively by the application of abstract combinatorial schemas, for example affixation rules. The success or failure of models in accounting for this particular issue can be used to draw more general conclusions about cognition and the degree to which abstract, symbolic representations and rules are psychologically and neurobiologically real. This debate can potentially be resolved using a neurophysiological paradigm, in which alternative predictions of the brain response patterns for lexical and syntactic processing are put to the test. We used magnetoencephalography (MEG) to record neural responses to spoken monomorphemic words ('*hide*'), pseudowords ('*smide*'), regular past-tense forms ('*cried*') and ungrammatical (overregularised) past-tense forms ('*flied*') in a passive listening oddball paradigm, in which lexically and syntactically modulated stimuli are known to elicit distinct patterns of the mismatch negativity (MMN) brain response. We observed an enhanced ('lexical') MMN to monomorphemic words relative to pseudowords, but a reversed ('syntactic') MMN to ungrammatically inflected past tenses relative to grammatical forms. This dissociation between responses to monomorphemic and bimorphemic stimuli indicates that regular past tenses are processed more similarly to syntactic sequences than to lexically stored monomorphemic words, suggesting that regular past tenses are generated productively by the application of a combinatorial scheme to their separately represented stems and affixes. We suggest discrete combinatorial neuronal assemblies, which bind classes of sequentially occurring lexical elements into morphologically complex units, as the neurobiological basis of regular past tense inflection.

Introduction

The neuropsychological representation of the English past tense, and specifically the distinction between regular and irregular past-tense forms, has been one of the most intensely debated issues in psycholinguistics for decades. One reason why the past tense has attracted so much attention is that it forms an ideal testing ground for theories about language and cognition in general. A distinction can be made between models that rely to some extent on symbols and abstract rules to explain mental operations, and models that dismiss rules in favour of a (connectionist) network that operates only based on associative memory. Both types of models make clear predictions about the processing of regular and irregular past tenses. The success of different models in accounting for past tense processing is therefore not only of significance within the domain of psycholinguistics, but provides a basis for wider-reaching conclusions about the interaction between storage and computation in the brain and the degree to which mental representations are symbolic in nature.

Pinker's (1991) (see also Pinker and Ullman, 2002) *Words and Rules* model is the most influential instantiation of a dual-route view on past tense processing, in which irregular past tense inflection involves only associative memory but regular forms are the product of an abstract affixation rule. According to this view, lexical items, affixes, and irregular past-tense forms are stored in declarative memory (Ullman et al, 1997), which is implemented as an associative network and relies mainly on temporal and temporo-parietal regions. By contrast, combinatorial processes such as affixation of regular past tenses are functions of procedural memory, subserved by the basal ganglia and inferior-frontal regions. A regular past-tense form is created by retrieving a stem and an affix from the lexicon, and applying a general merging operation on these elements. This type of model thus intuitively explains the common pattern of overregularisation of affixation (e.g. 'goed'), which occurs both in child language acquisition (Marcus et al, 1992) and in adults prompted to inflect pseudoverbs (Prasada and Pinker, 1993).

Furthermore, evidence in favour of a dual-route mechanism is provided by neuropsychological data from both neurological patients and healthy subjects. Lesion studies have revealed dissociations between

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regular and irregular inflection in patient groups with different neurological disorders (Marslen-Wilson and Tyler, 1997; Ullman et al, 1997). Patients with temporal lobe damage, for example as a result of Alzheimer's disease, are typically impaired on irregular forms. Decreased functioning of the basal ganglia or inferior frontal cortex, such as found in Parkinson's patients, on the other hand, induces more problems with regular than irregular inflection. This selective impairment of either regular or irregular inflection strongly suggests that these processes rely on distinct neurobiological systems.

Electrophysiological findings from healthy subjects have been interpreted as supporting the idea that regular past tense forms are decomposed by morphological syntax-like rules, whereas irregulars are processed like monomorphemic words. Several studies have found a reduction of the N400 component to regular verb stems primed by their past tense form, but observed no such priming effect from irregular past tenses to their stems (Münte et al., 1999; Rodriguez-Fornells et al., 2002; Weyerts et al., 1996). This suggests that the stem is indeed included in the regular past form, but not in the past form of irregulars. Studies using violation paradigms converge on the finding that regularisation of irregular verbs and nouns elicits a Left Anterior Negativity (LAN) or similar deflections, which is consistently evoked by morphological or syntactic violations and thus has been interpreted as evidence of morphosyntactic decomposition (Gross et al., 1998; Morris and Holcomb, 2005; Newman et al., 2007; Penke et al., 1997; Rodriguez-Fornells et al., 2001; Weyerts et al., 1997). Regular verbs with an irregular past tense affix on the other hand appear to be analysed as pseudowords, as suggested by N400 effects (Morris and Holcomb, 2005; Weyerts et al., 1997) and the absence of any LAN-like effects (Gross et al., 1998; Newman et al., 2007; Penke et al., 1997; Rodriguez-Fornells et al., 2001).

However, as Rumelhart and McClelland (1986) famously showed, a connectionist network storing all verb forms as patterns of interconnected phonemic units can simulate rule-like behaviour without the implementation of rules, and is therefore more parsimonious than dual-route models. Proponents of the connectionist view have argued that dissociations in neural activity in healthy participants and selective impairments in neurological patients can be explained without a dual mechanism, by positing that regular and irregular inflection rely to a different extent on phonological and semantic representations, respectively, rather than on distinct memory systems (Burzio, 2002; Bird et al., 2003; Joanisse and Seidenberg, 1999, 2005). Damage to the semantic representation of a word will affect irregular forms more than regular ones, whereas a phonological deficit selectively causes impaired regular inflection due to the larger phonological complexity of regular past tenses. When phonological complexity is controlled for, dissociations between irregular and regular past tense processing are weaker both in the performance of aphasic patients (Bird et al., 2003) and the neural response of healthy subjects (Joanisse and Seidenberg, 2005).

In response, Pinker and Ullman (2002) posited that the semantic module implemented by Joanisse and Seidenberg (1999) is in fact a lexicon, and that its selective impairment leading to damaged irregular inflection is precisely what dual-route models predict. Furthermore, Pinker and Ullman (2002b) point out that although controlling for the phonological complexity of regulars is evidently an important issue, Bird et al. (2003) may have introduced an opposite confound by including regular items with a more complex relation between stem and past tense form than those used in previous studies, and regular items that rhymed with irregulars, which are more likely to be stored lexically than more typical regular forms. Finally, whilst differences between irregular and regular processing in the Bird et al. (2003) data disappeared in several tasks, they remained in others, complicating the interpretation of their results.

Thus, although it appears that neural and behavioural dissociations are more easily explained by dual-route than by single-mechanism models of past tense processing, results are rather mixed and the most robust findings can be simulated by both types of models[1]. This is especially true for behavioural data, given that at least some rule-like behaviour does not require actual rules. A focus on neurophysiological data may therefore be more fruitful. One way to potentially distinguish between competing accounts of past tense processing is to use electro- or magneto-encephalography (EEG and MEG), which can track highly dynamic neural processes linked to linguistic processing with millisecond precision. As connectionist and dual-route models agree to a large extent about the associative nature of irregular past tense storage, we focus here on the more controversial issue of regular inflection. To study the nature of this process, we employed a mismatch negativity design, which has been applied successfully to similar questions in recent years.

The mismatch negativity (MMN) is an early (100–200 ms) evoked component visible in MEG and EEG recordings, elicited by unexpected 'deviant' stimuli which are infrequently presented in a sequence of repeated 'standard' stimuli (Näätänen, 2001). It is obtained by subtracting the response to standard stimuli from the more negative-going response to deviant stimuli, producing a negative (in EEG) peak in the difference curve. The MMN is elicited even in the absence of overt attention to auditory stimuli and is therefore especially useful for investigating the nature of lexical representations and processing in the brain without the need to employ (potentially confounding) tasks such as lexical or semantic decision (for a review, see Pulvermüller and Shtyrov, 2006; Shtyrov and Pulvermüller, 2007). The amplitude of the MMN is modulated by various linguistic properties of the deviant stimulus. Crucially, in addition to attention independence, the MMN paradigm allows for strict control of several important factors in neurolinguistic experiments: (1) by using a small set of tightly matched stimuli it removes stimulus variance, and thus provides a high signal-to-noise ratio and removes smearing introduced by large stimulus groups, which allows for unprecedented scrutiny of brain responses; (2) as a difference response elicited by acoustic deviance, the MMN paradigm allows for unique experimental designs where the same acoustic contrast can be incorporated into different deviant-standard linguistic contexts, thereby ruling out purely acoustic/phonetic influences on any differential response patterns. Comparing MMN responses elicited by deviants in different conditions has therefore been shown to be a useful method of investigating language processing.

Two distinct but complementary MMN patterns are especially relevant for the current study. First, the lexical MMN is an enhanced MMN response to deviant stimuli which are meaningful words known to the participant, compared with acoustically and phonologically matched meaningless pseudoword stimuli. This so-called lexical MMN enhancement activation is considered to stem from automatic activation of a pre-existing neuronal memory trace for words (Korpilahti et al., 2001; Pettigrew et al., 2004; Pulvermüller et al., 2001; Shtyrov and Pulvermüller, 2002a; Sittiprapaporn et al., 2003). These word-related memory traces are realised as distributed, strongly interconnected circuits of neurons formed in the processes of associative learning, which strengthens mutual connections between participating parts of the network. These traces are robust enough to be activated automatically whenever the respective word is presented, even if it is not specifically attended to, as is the case in a typical passive MMN paradigm (Shtyrov, 2010). Naturally, previously unfamiliar pseudowords do not have an underlying memory trace and thus elicit reduced activation in passive MMN designs.

Second, the syntactic MMN is a distinct pattern that emerges when comparing MMN responses with deviants which are well-formed syntactic sequences, to responses elicited by ungrammatical sequences. Whereas well-formed monomorphemic stimuli elicit enhanced MMN

[1] Note that although non-connectionist single-mechanism models of morphology have been proposed (e.g. Bybee, 1985), with regard to the issue at hand the predictions made by all single-mechanism models are identical since they make no fundamental distinction between processing of regular and irregular morphology.