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Probabilistic orthographic cues to grammatical category in the brain

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ABSTRACT

What helps us determine whether a word is a noun or a verb, without conscious awareness? We report on cues in the way individual English words are spelled, and, for the first time, identify their neural correlates via functional magnetic resonance imaging (fMRI). We used a lexical decision task with trisyllabic nouns and verbs containing orthographic cues that are either consistent or inconsistent with the spelling patterns of words from that grammatical category. Significant linear increases in response times and error rates were observed as orthography became less consistent, paralleled by significant linear decreases in blood oxygen level dependent (BOLD) signal in the left supramarginal gyrus of the left inferior parietal lobule, a brain region implicated in visual word recognition. A similar pattern was observed in the left superior parietal lobule. These findings align with an emergentist view of grammatical category processing which results from sensitivity to multiple probabilistic cues.

1. Introduction

During both language acquisition and normal adult communication decisions about the grammatical status of individual words are vital, albeit made without conscious awareness (Gerken, Wilson, & Lewis, 2005; Pinker, 1984; Sereno & Jongman, 1990; Shi, Morgan, & Allopenna, 1998). The differentiation between nouns and verbs, in particular, is perhaps the most common grammatical distinction across the world's languages (Baker, 2001). This is a testament to the fact that effective communication relies on an understanding of these grammatical categories. The status of a word as a noun or a verb is often signaled by the syntactically constraining context of a sentence: "Laurie took the *prune* out of the fruit bowl and ate it" (Folk & Morris, 2003). However, the presence of cues to grammatical category at the phrasal/sentence level does not preclude the existence of other cues; for example, cues that operate at the single word level (Monaghan, Chater, & Christiansen, 2005). In fact, there is growing evidence of probabilistic differences in both the sound structure (i.e., phonology) and the written representation (i.e., orthography or spelling) of individual words from different grammatical categories. The discovery of probabilistic cues to grammatical category operating within individual words, facilitated by the advent of large corpora and powerful analysis techniques, represents a significant challenge to assumptions about arbitrariness between a word's form (e.g., the way it is spelled) and a word's function (e.g., its status as a noun or a verb). For the first time, this study reports on the neural processing of these probabilistic cues.

1.1. Probabilistic cues to grammatical category

Analyses of English, Dutch, French and Japanese have revealed probabilistic phonological cues to grammatical category (Monaghan, Christiansen, & Chater, 2007). Behavioural sensitivity to cues embedded within single words has been demonstrated by showing that nouns exhibiting phonology that is typical of that class (e.g., *marble* which has a sound structure typical of nouns) are read more quickly than nouns exhibiting phonology that is atypical of the class (e.g., *insect* which has a sound structure that is atypical of nouns). This happens when these words are presented in the same syntactic context: "The curious young boy saved the *marble/insect* that he found on the playground" (Farmer, Christiansen, & Monaghan, 2006). A parallel body of work has revealed sensitivity to orthographic markers of grammatical category (Arciuli & Cupples, 2006, 2007; Kemp, Nilsson, & Arciuli, 2009). A word such as *reminisce* exhibits a combination of letters that is highly typical of verbs and elicits a processing advantage during reading tasks compared with a word such as *gallivant* that exhibits a spelling pattern that is atypical for verbs (Arciuli & Monaghan, 2009). The presence of probabilistic markers of grammatical category is consistent with a contemporary view of language processing as an example of implicit learning of statistical regularities present in language input which is optimised through sensitivity to multiple cues operating at a number of different levels (syntactic, semantic, and form-based such as phonological and orthographic).

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As far as we are aware, ours is the first study to examine the neural processing of probabilistic orthographic cues to grammatical category operating within individual words. However, cortical processing of nouns and verbs as grammatical entities is a heavily debated topic. An early hypothesis proposed that specific areas or modules are dedicated to the separate processing of each of these two grammatical classes. A recent review of the neuroimaging evidence relevant to a fronto-temporal dichotomy between verb and noun processing revealed numerous inconsistencies (Crepaldi, Berlingeri, Paulesu, & Luzzatti, 2011). An alternative approach emphasises an emergentist view whereby grammatical category distinctions emerge from a combination of variables including both semantic constraints and co-occurrences within language, including distributional cues at the phrasal level and probabilistic cues within words (Vigliocco, Vinson, Druk, Barber, & Cappa, 2011).

We drew on research by Arciuli and Monaghan (2009) indicating that there is a rich source of probabilistic information pertaining to grammatical category in the orthography of trisyllabic English nouns and verbs. Following on from previous corpus and behavioural work on English disyllables (Arciuli & Cupples, 2006, 2007; Kemp et al., 2009), Arciuli and Monaghan focussed on words' beginnings (the letters corresponding to the onset and first vowel) and also their endings (the letters corresponding to the rime of final syllable) in an analysis of the 14,638 unambiguous trisyllabic nouns and verbs in the CELEX language database (Baayen, Piepenbrock, & Gulikers, 1995). The analyses revealed 581 distinct beginnings and 946 distinct endings.

Some examples of the way certain combinations of letters are probabilistically related to grammatical category are as follows: The beginning *ca-* is a predictor of nouns, with 2.4% of all nouns beginning with this cue (compared to only 1.4% of verbs). On the other hand, *be-* is a predictor of verb status, beginning 1.6% of all verbs (compared to 0.5% of nouns). The ending *-ate* occurred in 4.5% of unambiguous verbs, but only 0.2% of nouns. Discriminant analysis revealed 73.5% of nouns and 56.4% of verbs (67.7% of words in total) were correctly classified on the basis of their beginning. Even more striking was that 97.5% of nouns and 83.1% of verbs (92.6% of words overall) could be correctly classified on the basis of their ending. Arciuli and Monaghan (2009) ran the same discriminant analyses on the subset of mono-morphemic words from CELEX (i.e., words that are comprised of only one morpheme such as 'cucumber'). Analysis of beginnings resulted in correct classification of 91.7% of nouns and 73.9% of verbs (91.1% of all words). In terms of endings, 99.0% of nouns and 69.6% of verbs were correctly classified (97.8% accuracy overall).

Importantly, Arciuli and Monaghan undertook behavioural testing to demonstrate that these orthographic cues influence processing of individual words during a visual speeded grammatical classification task (noun/verb; Exp. 1) that requires explicit decisions about grammatical category. More interestingly, they showed the same results during a lexical decision task (word/nonword; Exp. 2) that does not require explicit decisions about grammatical category to be made. In the grammatical classification task response times (RTs) were slowest for words with inconsistent endings and beginnings (1107 ms), followed by words with just inconsistent endings (1085 ms), and just inconsistent beginnings (1068 ms), compared to words with consistent endings and beginnings (1049 ms). As expected, in the lexical decision task RTs were faster overall; however, the same pattern of differences across conditions was observed. RTs were slowest for words with inconsistent endings and beginnings (950 ms), followed by words with just inconsistent endings (924 ms), and just inconsistent beginnings (899 ms), compared to words with consistent endings and beginnings (893 ms).

This response pattern across these two tasks is consistent with the general hypothesis that processing is slowed incrementally as more inconsistent orthographic information is encountered during visual word recognition. The relatively greater emphasis on word endings as cues to grammatical category aligns with proposals that the requirement to uniquely identify the word as quickly as possible may force shared information, such as that relating to grammatical category membership, to be represented more prominently at the ends of words rather than the beginnings (Arciuli & Monaghan, 2009; see also Hawkins & Cutler, 1988, for a similar explanation for end-effects in speech processing). Recent computational modelling studies of reading have also revealed the importance of word endings (e.g., Arciuli, Monaghan, & Seva, 2010).

Arciuli and Monaghan (2009) suggested that the similar findings across tasks provide constraints for models of lexical processing and reading: "higher levels of processing, such as grammatical class, have an influence on lexical access even when grammatical class is not directly probed, as in the lexical decision task. Such results are readily consistent with parallel distributed processing models of reading (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996), where multiple, interacting levels of representation can be available to the reading system." (pp. 88–89).

1.2. The current study

In the current study, we sought to investigate the brain's processing of probabilistic orthographic cues to grammatical category using the same visual lexical decision task and stimuli reported by Arciuli and Monaghan (2009) with functional magnetic resonance imaging (fMRI). Two plausible candidate regions for processing probabilistic orthographic cues are identifiable in the left hemisphere - the inferior parietal lobule (IPL) and inferior occipito-temporal cortex – as both have been implicated in processing of orthographic features across lesion and neuroimaging studies (e.g., Dehaene & Cohen, 2011; Déjerine, 1891, 1892; Geschwind, 1965; Philipose et al., 2007; Price, in press). Whether the left occipito-temporal cortex processes word-specific orthographic representations and/or sublexical properties of words selectively or in interaction with higher order language areas remains a topic of considerable debate (e.g., Dehaene & Cohen, 2011; Price & Devlin, 2011; Vogel, Petersen, & Schlaggar, in press).

Two fMRI studies have examined sublexical orthographic familiarity by employing nonword letter strings with either increasingly familiar (or probable) bigrams and/or quadrigrams, with both revealing increased activation in the left inferior occipito-temporal cortex (Binder, Medler, Westbury, Leibenthal, & Buchanan, 2006; Vinckier et al., 2007). Findings with real words have been mixed. For example, Graves, Desai, Humphries, Seidenberg, and Binder (2010) investigated correlations with bigram frequency in monosyllabic words, finding increasing activity with decreasing bigram frequency in the left supramarginal gyrus (a sub-region of the inferior parietal lobule) while participants read the words aloud during fMRI. However, they found no such relationship in the left occipito-temporal cortex. Hauk, Davis, and Pulvermüller (2008) failed to find any occipito-temporal activity correlated with orthographic typicality (a composite measure of bigram and trigram frequency) during silent reading of monosyllabic words, although they did find increased activity for more typical words in the medial portion of the superior parietal lobule (precuneus). Finally, Woollams, Silani, Okada, Patterson, and Price (2010) identified a left occipital region that demonstrated increased activity for less typical words during visual lexical decision. However, as the authors acknowledged, this region was posterior to the occipito-temporal cortex region typically reported in fMRI studies of nonword orthography (e.g., Binder et al., 2006; Vinckier et al., 2007).

Given the above, we predicted that we might find differential activation in left occipito-temporal and inferior parietal regions