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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 for trisyllabic nouns and verbs that contain orthography varying according to consistency with their grammatical category. Following Binder et al.'s (2006) results we thought we might observe linear decreases in activity associated with increasing orthographic inconsistency.

2. Method

2.1. Participants

Seventeen volunteers were recruited from among University of Queensland (UQ) students and staff (12 female, mean age 20.8 years, SD = 3.5). All were right-handed native English speakers, with no history of neurological or psychiatric disorder, substance dependence, or known hearing deficits. All had normal or corrected-to-normal vision. Written informed consent was obtained for all participants prior to commencing the experiment, and the UQ medical research ethics committee approved the experimental protocol.

2.2. Materials

The critical stimuli comprised the same 80 trisyllabic words (40 nouns and 40 verbs) identified by Arciuli and Monaghan's (2009) corpus analysis of the CELEX English language database. In that study, the consistency of each beginning and each ending of trisyllabic nouns and verbs, with respect to whether that particular orthographic string was consistent with that word's own grammatical category or of the opposing grammatical category, was determined using a 50% criterion. Of the 80 trisyllabic words, 20 had consistent cues in their beginnings and their endings (doubly consistent cues; e.g., *entertain* is a verb and both its beginning *e-* and ending *-ain* are associated with verb status), 20 had consistent cues only in beginnings (endings were associated with the other grammatical category; e.g., *upholster* is a verb with a beginning *u-* that is associated with verbs but its ending *-er* is more strongly associated with nouns), 20 had consistent cues only in endings (beginnings were associated with the other grammatical category; e.g., *persecute* is a verb with an ending *-ute* that is strongly associated with verbs but also has a beginning *pe-* that is more strongly associated with noun status), and 20 had cues that were inconsistent with their actual grammatical status (doubly inconsistent as both their beginnings and endings were associated with the other grammatical category; e.g., *jettison* is a verb but its beginning *je-* and its ending *-on* are typically seen in nouns). Within each of these four word sets there were 10 nouns and 10 verbs.

As reported by Arciuli and Monaghan (2009), analyses including beginning cues (consistent/inconsistent), ending cues (consistent/inconsistent), and grammatical class as factors ($2 \times 2 \times 2$ ANOVAs) demonstrated that the experimental stimuli were matched on overall length (number of letters), length of beginnings and length of endings (number of letters), written frequency of the whole word, orthographic neighbourhood size, and imageability. In terms of these dependent variables there were no main effects of beginning cue or ending cue and no significant interactions amongst these variables and grammatical class. There was a main effect of grammatical class with regard to the dependent variable of morphological family size ($F[1,72] = 53.91$, $p = .0001$). As would be expected, verbs exhibited a larger morphological family than nouns. There were no significant interactions involving morphological family size. For the current study we also examined the bigram frequency (type) of experimental stimuli. A $2 \times 2 \times 2$ ANOVA revealed no significant differences. This was also the case using token counts.

We used the same trisyllabic nonwords used by Arciuli and Monaghan (2009). These obeyed the phonotactic constraints of English (e.g., 'pelody', 'gorminal'). Words and nonwords were similar in terms of overall length and bigram frequency. Our experimental stimuli had a mean length of 8.4 letters (SD = .85) and a mean bigram frequency (type) of 52.72 (SD = 26.50). Nonwords had mean length of 7.63 letters (SD = 1.12) and a mean bigram frequency (type) of 54.97 (SD = 27.19).

Words and nonwords were randomly distributed into different lists of 160 items using the Mix program (van Casteren & Davis, 2006). Note: For seven participants, only 19 words that had inconsistent beginnings along with consistent endings were presented (due to a coding error resulting in a repeat of a noun or nonword). Words were presented in black font on a white background and projected using a BenQ SL705X projector onto a screen at the foot of the bore of the MRI system that participants viewed through a mirror mounted on the head coil, subtending approximately 10° of the visual arc.

2.3. Procedure

Participants were presented with a task in which they were asked to identify whether a letter string on the screen was a 'word' or a 'nonword', indicating their response by selecting the right or left mouse button (counterbalanced between participants). Participants were allowed to practice the task on a computer before entering the scanner, and prompted to respond as quickly and as accurately as possible. In the scanner, participants completed two runs of the task in which half of the pseudorandomized word list was presented in each session. All trisyllabic word/nonword stimuli were presented in black Times New Roman 42-point font on a white background. Trials consisted of a crosshair presented for 500 ms followed by the trisyllabic word/nonword until the participant's lexical decision response was logged or a 2000 ms timeout in the case of omitted responses. A blank inter-trial interval (ITI) was jittered pseudo-randomly using eight different delays (2700, 3225, 3750, 4275, 4800, 5325, 5850, and 6375 ms; mean 4537 ms) to optimise the estimation of the BOLD response. Participants were in the scanner for a total of approximately 40–45 min.

2.4. Image acquisition

Images were acquired using a 4 T Bruker Medspec system with a transverse electromagnetic head coil for radio-frequency transmission and reception (Vaughan et al., 2002). Functional T2*-weighted images depicting BOLD contrast (64×64 matrix, 3.6×3.6-mm voxels) were acquired using a gradient-echo EPI sequence optimised for image quality and noise reduction (McMahon, Pringle, Eastburn, & Maillet, 2004). In each of two consecutive runs, 275 image volumes of 36 axial 3.5-mm slices (0.1-mm gap) were acquired (repetition time = 2.1 s, echo time = 30 ms, flip angle = 90°). The first five volumes were discarded from each series. Foam padding in the head coil was used to limit head movement. To correct geometric distortions, a point-spread function (PSF) mapping sequence was acquired prior to the functional EPI acquisitions (Zaitsev, Hennig, & Speck, 2003). A structural three-dimensional T1-weighted image was also acquired using a magnetisation-prepared rapid acquisition gradient-echo (MPRAGE) sequence (TI = 700 ms, TR = 1500 ms, TE = 3.35 ms, 256^3 matrix, 0.9-mm^3 voxels).

2.5. Image analysis

Image preprocessing and analysis were conducted with statistical parametric mapping software (SPM8; Wellcome Department of Imaging Neuroscience, Queen Square, London, UK). All volumes from each session were first resampled using generalised interpolation to the acquisition of the middle slice in time to correct for the interleaved acquisition sequence, then realigned to the first volume of the initial session using the INRIAlign toolbox (Freire, Roche, & Mangin, 2002). A mean image was generated from the realigned series, and coregistered to the T1-weighted image to which the 'New Segment' procedure was next applied in SPM8. The 'DARTEL' toolbox (Ashburner, 2007) was employed to create a custom group template from the grey and white matter images and individual flow fields that were used to normalise the realigned fMRI volumes to the MNI atlas T1 template. The resulting images were resampled to 2 mm^3 voxels and smoothed with an 8 mm FWHM isotropic Gaussian kernel. Global signal effects were then estimated and removed using a voxel-level linear model (Macey, Macey, Kumar, & Harper, 2004).

We conducted a two-stage, mixed effects model statistical analysis. Trial types corresponding to correct responses were defined for beginnings/endings × consistent/inconsistent cues for each grammatical category in addition to nonwords. These were modelled as effects of interest with delta functions representing each onset, along with a nuisance regressor consisting of error onsets, and convolved with a synthetic hemodynamic response function (HRF) and accompanying temporal and dispersion derivatives. Standard high (1/128 Hz) and low pass filtering with an autoregressive (AR1) model were applied. Linear contrasts were applied to each participant's parameter estimates at the fixed effects level, for correct responses, then entered in a second level group repeated measures analysis of variance (ANOVA) in which covariance components were estimated using a restricted maximum likelihood (REML) procedure to correct for non-sphericity (Friston et al., 2002). Mean response times (RTs) in each condition for each participant were entered as covariates to permit condition-specific effects to be estimated (e.g., Binder et al., 2006; Woollams et al., 2010).

As we had a priori hypotheses concerning roles for the left inferior occipitotemporal cortex and left inferior parietal lobule with respect to processing of orthographic consistency, a height threshold of $p < .001$ for significance was adopted in conjunction with a spatial cluster extent threshold that was family-wise error (FWE) corrected for multiple comparisons in four independent regions of interest (ROIs). For the left inferior occipitotemporal cortex, two ROIs (8 mm radius spheres) were centered on Binder et al.'s (2006) and Vinckier et al.'s (2007) reported peaks with coordinates ($x = -44$, $y = -60$, $z = -12$) and ($x = -40$, $y = -48$, $z = -22$), respectively. A left posterior occipital ROI (8 mm radius sphere) was also centered on the coordinates ($x = -34$, $y = -86$, $z = -8$) from Woollams et al. (2010). For the left inferior parietal lobule, an anatomical ROI encompassing both supramarginal and angular gyri was selected from the Hammers et al. (2003) probabilistic atlas. In addition, we conducted an exploratory analysis with a height threshold of $p < .001$ for significance in conjunction with a cluster extent threshold FWE corrected for multiple comparisons across the whole brain.

3. Results

3.1. Behavioural data

The RTs and error rates for the 17 participants were analysed. Trials scored as errors were excluded from analysis. No RT outliers were found using <200 ms and >2000 ms as exclusion criteria. A repeated measures ANOVA on mean RTs revealed a significant main effect of lexicality $F(1, 16) = 21.5$, MSE = 3096, $p < .001$, $\eta^2 = .57$, with the typical pattern of decisions for nonwords (mean 957 ms) being slower than those for words (mean 868 ms). The reverse pattern was found for mean error rates (word 28.2%, nonword 8.4%) $F(1, 16) = 88.67$, MSE = .004, $p < .001$, $\eta^2 = .85$.

A 2 × 2 × 2 repeated measures ANOVA with the three factors of grammatical category (noun/verb), beginning cues (consistent/inconsistent) and ending cues (consistent/inconsistent) did not reveal a significant main effect of grammatical category or any interactions. Therefore, as per Arciuli and Monaghan (2009), we collapsed the data across grammatical category. Following our hypothesis that processing would be slowed incrementally as more inconsistent orthographic information is encountered during visual word recognition, with such information also represented more prominently in word endings, we investigated a numerical linear trend in the mean RTs collapsed across grammatical category corresponding to doubly inconsistent > ending inconsistent > beginning inconsistent > doubly consistent (Fig. 1). We determined the significance of this trend via the regression analysis for repeated measures data recommended by Lorch and Myers (1990, Method 3, p. 153). A linear regression analysis was computed for each individual participants RTs, with level of orthographic consistency as predictor variable. In a final step, a t-test was performed to test whether the regression weights of the group differed significantly from zero. A significant linear effect was found with $t(16) = 19.17$, $SE = 47.41$, $p < .001$, $d = .97$.[1] We went back to the RTs from Exp. 2 of Arciuli and Monaghan's (2009) study and conducted the same repeated measures linear regression analysis. That dataset also revealed a significant linear effect with $t(28) = 28.33$, $SE = 34.09$, $p < .001$, $d = 1.13$.

We investigated a numerical linear trend in the mean error rates using the same regression analysis for repeated measures data as per the RTs above (Fig. 1). A significant linear effect was

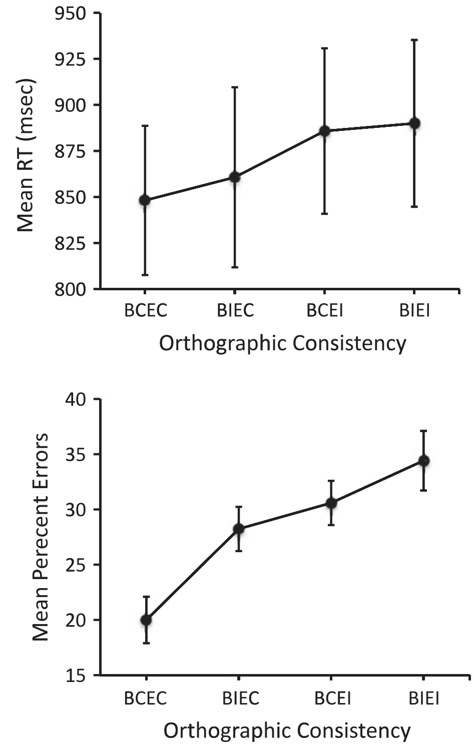

Fig. 1. (Top) Mean response times (RT) as a function of beginning and ending cue consistency. (Bottom) Mean percent error rates as a function of beginning and ending cue consistency. Key: BCEC (beginning consistent, ending consistent: doubly consistent), BIEC (beginning inconsistent, ending consistent), BCEI (beginning consistent, ending inconsistent), BIEI (beginning inconsistent, ending inconsistent: doubly inconsistent). Bars represent standard errors.

[1] As Lorch and Myers (1990) note, their method does not provide values of R^2, and simply averaging R^2 across participants would provide a distorted measure of slope. Hence, they do not recommend reporting it. Subsequent authors (e.g., Thompson, 2008) have proposed reporting of Cohen's d as a measure of effect size, given that RTs and error rates are DVs with intuitive meaning. This is the approach adopted here.

Table 1
Cerebral regions showing significant BOLD signal increases across all word conditions relative to the fixation baseline.

	Coordinates (*xyz*)			*Z* score	Cluster Size (Voxels)
Left fusiform, inferior and middle-inferior occipital gyri	−38	−56	−18	6.66	3024
Bilateral calcarine gyri	2	−78	14	5.34	1621
Left insula, inferior frontal and precentral gyri	−38	16	−4	5.56	2961
Left postcentral gyrus, superior and inferior parietal lobules	−40	−42	60	5.77	1835
Left superior medial frontal gyrus	−2	18	42	5.75	987
Left superior frontal gyrus	−22	−8	54	4.35	293
Right cerebellum	42	−50	−36	5.91	2325

Height threshold $p < .001$ and $p < .05$ cluster FWE corrected (whole brain; cluster threshold 278 voxels).

found with $t(16) = 6.88$, $SE = .025$, $p < .001$, $d = 1.27$. Similarly, when analysed the same way, the error rates from Exp. 2 of Arciuli and Monaghan's (2009) study also revealed a significant linear effect with $t(28) = 16.18$, $SE = 2.26$, $p < .001$, $d = 1.29$.

3.2. Imaging data

The fMRI datasets from two participants were excluded due to excessive motion, defined as exceeding one voxel dimension in any direction within session. Regions demonstrating significant BOLD signal increases for words across all conditions relative to rest were first investigated (e.g., Vinckier et al., 2007), revealing extensive activation in left occipitotemporal cortex, bilateral calcarine gyrus, left insula through inferior frontal and precentral gyrus, left superior frontal gyrus, left inferior and superior parietal cortex and in right cerebellum (see Table 1).

A $2 \times 2 \times 2$ repeated measures ANOVA with the three factors of grammatical category (noun/verb), beginning cues (consistent/inconsistent) and ending cues (consistent/inconsistent) did not reveal a significant main effect of grammatical category or any interactions in the fMRI data. Following Binder et al. (2006) and Vinckier et al. (2007), we investigated possible linear trends in the fMRI data according to orthographic cue consistency, collapsed across grammatical category, by constructing linear contrasts for doubly inconsistent < ending inconsistent < beginning inconsistent < doubly consistent conditions and the inverse, including lexical decision RTs as covariates to identify condition specific effects (Binder et al., 2006; Woollams et al., 2010). In the left inferior parietal cortex anatomical ROI, significant linear reductions in activity with increasing orthographic inconsistency were identified in a cluster of voxels with a peak in the suparamarginal gyrus. No significant activity was observed in this ROI for the inverse contrast. Nor was any significant activity in either direction detected in the two left occipito-temporal ROIs adapted from Binder et al. (2006) and Vinckier et al. (2007), respectively, or in the left occipital ROI from Woollams et al. (2010) using SVC. Employing correction for multiple comparisons at the whole brain level, the exploratory analysis revealed significant decreases in activity in the same left supramarginal gyrus cluster identified in the anatomical ROI analysis above, in addition to a novel cluster in the left superior parietal lobule (see Table 2, Fig. 2). No significant activity was observed for the inverse contrast using correction for multiple comparisons at the whole brain level.

4. Discussion

The distinction between nouns and verbs is a striking commonality given the diverse nature of the world's languages. Even those who are skeptical of linguistic universals acknowledge that this particular distinction may well be found in all languages (Evans & Levinson, 2009). This distinction is represented syntactically and semantically. More recent discoveries point to form-based distinctions between nouns and verbs (Farmer et al., 2006). Here we drew on recent corpus and behavioural research demonstrating that there is a rich source of probabilistic cues to grammatical category in the way individual words are spelled. In the first study of its kind we sought to elucidate the brain's processing of these cues.

Specifically, we investigated the neural processing of probabilistic orthographic cues to grammatical category in trisyllabic English nouns and verbs. Stimuli varied in whether their beginnings and their endings were consistent with other words from that grammatical category (as determined by the corpus analyses conducted by Arciuli & Monaghan, 2009). Words were either doubly consistent, consistent only in terms of their endings, consistent only in terms of their beginnings, or doubly inconsistent. Importantly, stimuli within these conditions were matched on both overall length and length of beginnings/endings, frequency, neighbourhood size, imageability, morphological family size and bigram frequency. Using the same stimuli and lexical decision task (word/nonword), we were successful in replicating the graded patterns of response times and error rates seen in Arciuli and Monaghan's (2009) behavioural study. Participants responded most quickly and made the fewest errors when reading individual words with doubly consistent cues, followed by words with consistent endings, words with consistent beginnings, and words with doubly inconsistent cues.

Neural processing of these cues indicated linear reductions in BOLD signal responses in the left supramarginal gyrus and superior parietal lobule for words as their orthographic inconsistency with their grammatical class increased. Thus, in addition to replicating the original behavioural findings of Arciuli and Monaghan (2009) in the current study, our fMRI data demonstrated that participants are sensitive to orthographic cues to grammatical category at the neural level, even when performing a task that does not require explicit decisions about the grammatical status of words.

As noted in the original study by Arciuli and Monaghan (2009), which used the same stimuli during a task that required explicit grammatical category judgments as well as during a lexical decision task (Experiments 1 and 2, respectively), these findings indicate that higher levels of representation, such as grammatical category, can influence lexical processing even when explicit judgments about grammatical status are not required. In both the Arciuli and Monaghan (2009) study and the current study there was no interaction involving grammatical category. Thus, our nouns and verbs appeared to be processed in a similar way. This is not surprising given that our orthographic consistency cues were determined in the same way for our noun and our verb stimuli and that the stimuli were matched on a number of variables (for nouns and for verbs *within* each of our four conditions: see Method where we refer to the results of $2 \times 2 \times 2$ ANOVAs). In terms of matching variables, the only significant difference between our nouns and verbs was in morphological family size where, as expected, verbs had a larger morphological family size than nouns. We did not see any neural correlates of this difference in morphological family size in our BOLD responses. Thus, our imaging results suggest that noun and verb networks are spatially intermingled, at least in so far as the spatial resolution available in 4T BOLD signals.

Table 2
Cerebral regions showing significant linear decreases in activity as a function of decreasing orthographic cue consistency.

	Coordinates (*xyz*)			*Z* score	Cluster size (voxels)
Left superior parietal lobule[a]	−22	−48	66	4.35	295
Left supramarginal gyrus[a,b]	−54	−22	24	4.05	253

Height threshold $p < .001$ and $p < .05$ cluster FWE corrected.
[a] Whole brain corrected (cluster threshold 253 voxels).
[b] Inferior parietal lobule (Hammers et al., 2003) small volume corrected (SVC; threshold 230 voxels).

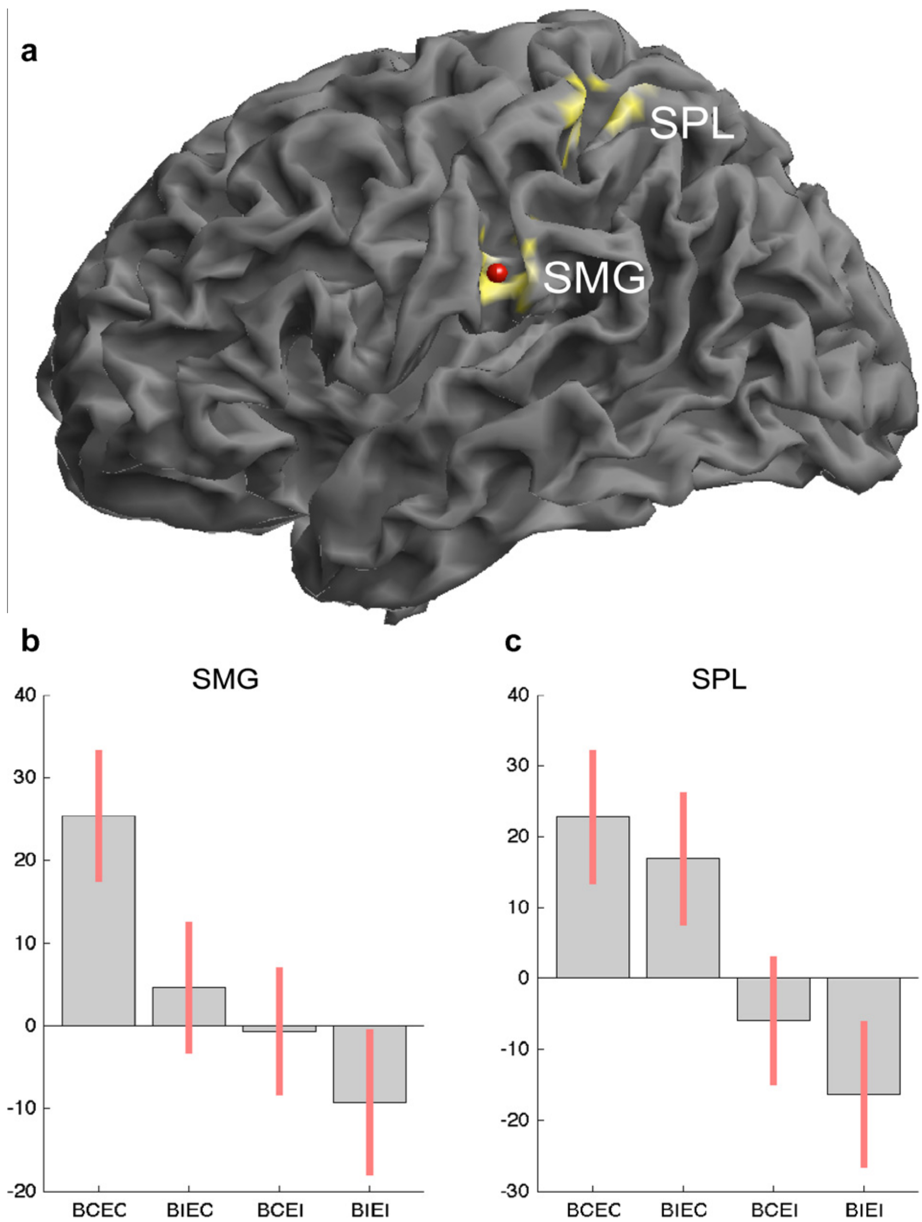

Fig. 2. (a) Three-dimensional rendering of the left hemisphere cortical surface showing inferior and superior parietal lobule regions demonstrating significant linear decreases in activity associated with increasing orthographic inconsistency with grammatical category. Activation is height thresholded at $p < .001$ and cluster extent thresholded at $p < .05$ FWE corrected for multiple comparisons at the whole brain level (cluster threshold: 253 voxels). The red dot indicates the peak maxima for the cluster in supramarginal gyrus (SMG). (b) Plot showing mean centred effect sizes across the consistency conditions at the peak voxel in the left SMG. (c) Plot showing mean centred effect sizes across the orthographic consistency conditions at the peak voxel in the left superior parietal lobule (SPL). Red bars indicate 90% confidence interval of the respective means. Key: BCEC (beginning consistent, ending consistent: doubly consistent), BIEC (beginning inconsistent, ending consistent), BCEI (beginning consistent, ending inconsistent), BIEI (beginning inconsistent, ending inconsistent: doubly inconsistent).

A role for the inferior parietal area in visual word form recognition has been established for some time, with lesions to either it or to the visual pathway linking occipito-temporal cortex with the inferior parietal lobule resulting in selective reading deficits (e.g., Déjerine, 1891, 1892; Geschwind, 1965; Philipose et al., 2007). Of note, in Philipose et al.'s (2007) voxel based lesion symptom mapping study of word and pseudoword reading, left supramarginal gyrus (SMG) dysfunction was the best predictor of impairment, followed by left occipito-temporal cortex. In a recent fMRI study, Graves et al. (2010) reported the opposite pattern of increased BOLD signal in left SMG associated with decreasing 'graphotactic probability' (bigram frequency) in monosyllabic words when a range of other variables were statistically covaried (frequency, consistency, imageability). Here, our experimental stimuli were matched on bigram frequency. We investigated 'probability' in a different, and perhaps more specific, sense – with reference to cues to grammatical category embedded in trisyllabic word beginnings and endings – using a factorial manipulation with carefully controlled stimuli.

Recent research with fMRI and TMS has ascribed a relatively specific role for the supramarginal gyrus (SMG) in terms of orthography-to-phonology conversion (e.g., Hartwigsen et al., 2010; Stoeckel, Gough, Watkins, & Devlin, 2009), and recent perspectives have linked the left SMG with a 'non-semantic phonological decoding route' during visual word recognition (see Price, in press). Therefore, it seems reasonable to conclude that the linearly decreasing activity in the left SMG associated with increasing orthographic cue inconsistency indicates a direct or indirect influence of orthographic cue probability on phonological decoding. Most contemporary models of visual word recognition include bidirectional connections between orthographic and phonological codes. However, these models have tended to focus on monosyllables.

We note that neighbourhood size manipulations do influence word naming and lexical decision latencies (e.g., Andrews, 1992; Yap & Balota, 2009) and have been associated with SMG activation in fMRI studies of speech production and perception tasks, and this has been interpreted as evidence for a role for the SMG in mediating competition at the level of the phonological word form (e.g., Peramunage, Blumstein, Myers, Goldrick, & Baese-Berk, 2011; Prabhakaran et al., 2006; but see Bullock-Rest et al., 2011 for a recent demonstration that aphasics with SMG lesions do not show impairments in lexically-conditioned phonetic variation). Graves et al. (2010) acknowledged that neighbourhood size might have been a potential confound in their study. Although the nouns and verbs in each of our four conditions were matched on neighbourhood size, trisyllabic words tend to have small neighbourhoods, and this was certainly the case with our stimuli.

Evidence for phonological competition in visual word recognition has also been provided by studies of syllable frequency effects in lexical decision, with slower responses observed for words starting with high- relative to low-frequency syllables (see Conrad, Tamm, Carreiras, & Jacobs, 2010 for a review and model of multisyllabic word recognition). However, while syllable frequency effects in lexical decision have been observed reliably in languages such as German, French and Spanish, thus far they have not been observed in English (e.g., Macizo & van Petten, 2007). In addition, fMRI studies manipulating syllable frequency in lexical decision and production tasks have typically reported null results, with none reporting SMG activation (e.g., Brendel et al., 2011; Carreiras, Mechelli, & Price, 2006; Riecker, Brendel, Ziegler, Erb, & Ackermann, 2008). Thus, an interpretation of our SMG activation in terms of competition among purely lexical-phonological candidates does not seem viable. Nor does an interpretation of the SMG activation in terms of morpho-syntactic processing seem viable, as the majority of studies of derivational marking/inflection in production and perception have implicated left middle temporal (MTG) and inferior frontal gyri (IFG) rather than the SMG (e.g., Joanisse & Seidenberg, 2005; Tyler, Marslen-Wilson, & Stamatakis, 2005; Yokoyama et al., 2006). Post hoc analyses of these two regions employing SVC with probabilistic ROIs (Hammers et al., 2003) did not reveal any significant effects of orthographic cue consistency. Consequently, we favour an interpretation of the SMG activation observed in terms of orthography-to-phonology procedures.

We acknowledge that the inability to detect any linear effect of orthographic cue probability in the left occipitotemporal region should be interpreted with caution, as it is a null result. Further, this null result should be interpreted in context with the significant activity observed in this region for the contrast of word reading relative to the fixation baseline, which is a typical result (e.g., Vinckier et al., 2007). Although inconsistent with the findings of the Binder et al. (2006) and Vinckier et al. (2007) fMRI studies employing bigram frequency manipulations in nonwords, the null result is nonetheless consistent with those of all three fMRI studies to date that manipulated bigram frequency/orthographic typicality in real words (Graves et al., 2010; Hauk et al., 2008; Woollams et al., 2010). It is worth reiterating that bigram frequency manipulations with real words have been shown to have no influence on latencies during lexical decision or reading aloud (e.g., Andrews, 1992; Yap & Balota, 2009). As such, we consider the overall pattern of evidence consistent with the proposal that, while sensitive to sublexical properties of words, the left occipito-temporal cortex is not sensitive to orthographic cues to a word's grammatical status and, by extension, is less likely to be specialised for processing words per se (e.g., Price & Devlin, 2011; Vogel et al., in press).

The exploratory whole brain analysis identified a cluster of voxels in the left superior parietal lobule that also demonstrated significant decreases in BOLD signal response to words with increasing cue inconsistency. Hauk et al. (2008) likewise identified a left superior parietal lobule region showing a similar pattern of responses in their study of orthographic typicality, albeit more medial to the one found here. The involvement of superior parietal regions during reading is often characterised in terms of the role of a dorsal attention system, reflecting the spatial selection and sequencing required for orthographic processing in visual word recognition (e.g., Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Pammer, Hansen, Holliday, & Cornelissen, 2006; see Price, in press). For example, Levy et al. (2008) identified increasing BOLD signal responses in both the left superior parietal lobule and SMG for consonant strings of increasing length. Hence, orthographic cues to grammatical category may influence the amount of attention directed to multisyllabic words, particularly when embedded in word endings. As the inconsistent cues are less informative with respect to grammatical category, less attention may be directed to them in visual word recognition, thus accounting for the decrease in activation observed.

One question arising from the current findings is to what extent the processing of probabilistic orthographic cues to grammatical category within individual words influences syntactic processing when distributional cues are readily available at the phrasal level. As noted in the Introduction, Farmer et al. provided a demonstration of behavioural sensitivity to probabilistic phonological cues to grammatical category that operate at the single word level even in sentential contexts (Farmer et al., 2006). Arciuli and Cupples (2006) examined the use of probabilistic cues to grammatical category in nonwords during sentence construction. In their corpus analysis of *disyllabic* nouns and verbs in the CELEX language database, they found probabilistic links between the spelling of words' endings and grammatical category membership. They created nonwords that contained these orthographic cues (e.g., the nonword *lanage* is noun-like because over 90% of disyllabic words ending in *-age* are nouns whereas the nonword *refend* is verb-like because around 80% disyllabic words ending in *-end* are verbs) and then asked participants to use these nonwords in a sentence. As expected, nonwords with noun-like endings were used as nouns significantly more often than nonwords with verb-like endings. In contrast, nonwords with verb-like endings were used as verbs significantly more often than nonwords with noun-like endings. It would be valuable to extend this behavioural research using fMRI.

5. Conclusion

The findings reported here provide, for the first time, a triangulation of data from corpus analyses, behavioural studies and brain imaging to support the conclusion that probabilistic orthographic cues to grammatical category play a role in lexical processing. Although the cognitive neuroscience literature on grammatical category has been concerned largely with identifying spatially discrete brain areas assumed to reflect modular representations of nouns versus verbs, with equivocal results (Crepaldi et al., 2011), the data presented here suggest that an emergentist approach (Vigliocco et al., 2011) may be a more promising avenue. The presence of cues to grammatical category that operate at a number of levels (syntactic, semantic, phonological, orthographic) aligns with a view of language processing as an example of statistical learning that is optimised through sensitivity to multiple cues.

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