Processing differences across regular and irregular inflections revealed through ERPs

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RUNNING HEAD: ERP DIFFERENCES ACROSS REGULAR AND IRREGULAR

INFLECTIONS

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Abstract

Research strongly suggests that printed words are recognized in terms of their constituent

morphemes, but researchers have tended to consider the recognition of derivations and inflections in

separate theoretical debates. Recently, Crepaldi et al. (2010) proposed a theory that claims to

account for the recognition of both derivations and inflections. We investigated brain potentials in

the context of masked priming to test two key predictions of this theory: (a) that regular inflections

should prime their stems to a greater degree than irregular inflections should prime their stems; and

(b) that priming for regular inflections should arise earlier in the recognition process than priming

for irregular inflections. Significant masked priming effects were observed for both regular and

irregular inflections, though these effects were greater for regular inflections. ERP data further

suggested that masked priming effects for regular and irregular inflections had different time

courses. Priming for regular but not irregular inflections emerged in a time window reflecting

processing up to 250 ms post target onset, and while priming for regular and irregular inflections

was observed in a time window reflecting processing 400-600 ms post target onset, these effects

arose earlier and were of greater magnitude for the regular inflections. These findings support a

form-then-meaning characterisation of the visual word processing system such as that proposed by

Crepaldi et al. (2010) and raise challenges for alternative approaches.

The vast majority of words in English, as in other languages, are built by combining and recombining a finite number of stems (e.g. clean) with a small set of inflectional (e.g. -ing, -ed, -s) and derivational (e.g. un-, -ish, -ly) affixes. These combinatorial processes account for around 85% of distinct English words (e.g. cleaned, cleaning, cleanly, unclean), and are also key to lexical productivity, accounting for around 70% of new words entering the language (e.g. bioweapon, arborist; Algeo, 1991). Yet, despite the importance of morphological processes across the world's languages, understanding how printed words comprising more than one morpheme are recognized has been relatively under-represented in the major theoretical models to date (e.g. Coltheart et al., 2001; Plaut et al., 1996).

There is now substantial evidence that printed words comprising more than one morpheme are recognized in terms of their morphemic constituents (e.g. darkness is recognized through the analysis of {dark} + {-ness}). However, there is still uncertainty around the precise nature of this decomposition process. One emerging theory is that morphologically-complex words undergo an initial rapid segmentation based on morphemes defined *orthographically*, and this segmentation process is followed sequentially by the activation of the semantic properties of those morphemes (Rastle & Davis, 2008; Rastle, Davis, & New, 2004). Some of the key evidence for this theory arises in the priming paradigm. When primes are masked and presented very briefly (42 ms), the recognition of stem targets is speeded by any prime that *appears* morphologically related, whether it is a genuine morphological relation (e.g. banker-BANK) or a pseudo-morphological relation (e.g. corner-CORN). Critically, priming in both of these cases is greater than that observed when there is a simple orthographic relation between primes and targets (e.g. brothel-BROTH), confirming the morphological nature of the effect (Longtin et al., 2003; Rastle et al., 2004; Kazanina et al., 2008; McCormick et al., 2008; see Rastle & Davis, 2008 for review). fMRI and electrophysiological data provide strong converging evidence for a morphological segmentation process insensitive to semantic factors (Gold & Rastle, 2007; Lavric et al., 2007; 2011; 2012; Morris et al., 2013) that

arises within around 190 ms of stimulus onset (Lavric et al., 2012).

However, virtually the whole of this body of literature on rapid *morpho-orthographic segmentation* (Rastle et al., 2004) concerns the processing of derived forms. English inflectional morphology presents an interesting case for investigation because of the need to consider not only regular infections (e.g. jumped, grows), which can be parsed orthographically into an identifiable stem and affix, but also irregular inflections (e.g. stole, geese) which cannot. Crepaldi et al. (2010) argued that because a stem cannot be extracted from irregular English inflections on the basis of morpho-orthographic segmentation, masked priming effects should not be expected for these kinds of stimuli (e.g. fell-FALL; geese-GOOSE). Yet, they did observe robust masked priming effects for irregular inflections. Further, in contrast to the derivational case (e.g. Rastle et al., 2004), this priming did not extend to pseudo-irregular inflections (e.g. bell-BALL; cheese-CHOOSE). Thus, it appears that masked priming effects for derivational items are largely insensitive to semantic factors (e.g. banker-BANK yields the same priming as corner-CORN) and require orthographic parsability, while masked priming effects for irregular inflectional items are sensitive to semantic factors (e.g. fell-FALL yields priming but bell-BALL does not) and do not require orthographic parsability.

These insights led Crepaldi et al. (2010) to propose a new theory of the recognition of printed words (see Figure 1), which claims that the seemingly inconsistent masked priming effects observed for derivations and inflections actually reflect similarity at different levels of representation. On this theory, letter strings undergo an initial morpho-orthographic parse before activating unique entries in an orthographic lexicon; activity in the orthographic lexicon is then passed on to a lemma level of representation that intervenes orthographic and semantic layers. Crucially, the lemma level in this theory follows research in the word production literature (e.g. Roelofs, 1992) in postulating that inflectional variants share a lemma (e.g. fall, falls, fell) while derivational variants (e.g. cleanly, cleanliness, unclean) do not. On this model, priming for banker-BANK and corner-CORN pairs arises at the morpho-orthographic level, while priming for fell-FALL (but not bell-BALL) arises at

the lemma level. Hence, this theory postulates that English regular inflections (e.g. falls) will activate representations of their stems at two levels (the morpho-orthographic level and the lemma level) while English irregular inflections (e.g. fell) will activate representations of their stems at only one level (the lemma level). This theory thus makes the strong prediction that (a) the magnitude of masked priming effects for regular inflections should be greater than those for irregular inflections; and (b) priming effects for regular inflections should arise earlier than priming effects for irregular inflections.[1]

---- Figure 1 about here ----

Morris and Stockall (2012) sought to test this prediction using the exquisite temporal resolution provided by EEG/ERP analysis. Using a 70 ms SOA, they measured lexical decisions to English stem targets preceded by masked identity, inflectional, orthographic neighbour, and unrelated primes. Critically, inflectional primes could be regular (e.g. jumped-JUMP) or irregular (e.g. fell-FALL). Analyses of the behavioural data revealed significantly greater priming from inflections than from orthographic control primes, irrespective of inflectional regularity. However, while priming from regular inflections (32±4 ms) did not differ from identity priming of the same stems (33±4 ms), priming from irregular inflections (13±3 ms) was significantly less than identity priming of the same stems (39±4 ms). Thus, the behavioural data appeared consistent with the first prediction above from the Crepaldi et al. (2010) theory. However, we note that priming effects for irregular and regular inflections were never compared directly, perhaps because of a confound between prime length and regularity (because regular past tense forms always have an additional –ed cluster, they were significantly longer than their irregular counterparts in this experiment, 6.08±.07 vs. 4.53±.08, F=88.41, p<.001). Unfortunately, these behavioural data were not consistent

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[1] It is important to note that this prediction about inflectional regularity depends on the particular characteristics of English inflectional morphology, whereby regular inflections preserve the stem and irregular inflections do not. In languages in which regular inflectional processes do not preserve the stem (and thus yield a form that cannot be segmented into stem and affix), the prediction is less clear (though see McCormick et al., 2008 for evidence that morpho-orthographic segmentation is robust to regular orthographic alterations to stem forms as a result of derivational processes).

with the ERP data, which revealed significant inflectional priming in both of the time windows studied (N250 and N400), but which revealed no significant interaction with regularity in either time window. Thus, while the behavioural data of Morris and Stockall (2012) appear consistent with the predictions of Crepaldi et al. (2010), the neurophysiological data offer no support either for a difference in the magnitude of regular and irregular inflectional priming or for a difference in their respective time-courses.

More recently, Fruchter, Stockall, and Marantz (2013) investigated the recognition of English regular and irregular inflections using masked priming combined with MEG. Using a much shorter SOA of 33 ms, they measured lexical decisions to stem targets preceded by identity, regular inflectional, irregular inflectional, pseudo-irregular, and unrelated primes. Their behavioural data revealed significant masked priming for both regular (23 ms) and irregular (14 ms) inflections. These data appear consistent with the predictions of Crepaldi et al. (2010) and the results of Morris and Stockall (2012), though again, no interaction statistic was reported, perhaps because of a confound between regularity and prime length (regular primes: 6.12±.44; irregular primes: 4.20±.83). The MEG data were more puzzling. Analyses of the M100 in a pre-determined fusiform ROI yielded significant priming for regular inflections; however, this was only the case when the regular inflectional and identity priming conditions were collapsed. Further, the direction of the priming effect was unexpected (greater fusiform activity for related primes). Analyses of the M170 in the same fusiform ROI yielded a significant priming effect when all conditions were combined, but again, the direction of this priming effect was unexpected, with greater activity observed for related primes than for unrelated primes. Based on these unexpected results, the authors identified another ROI that showed M170 priming in the expected direction for the identity and regular inflectional conditions. This ROI also showed irregular inflectional priming in the expected direction, though whether that priming differed from the priming observed for regular inflections was not reported. Analyses of the M350 in a middle temporal ROI yielded significant priming for

the identity, regular inflectional and irregular inflectional conditions in the expected direction, though no interaction statistic was reported comparing the magnitude of priming in these conditions. Overall, then, while the behavioural data of Fruchter et al. (2013) appear consistent with the predictions of Crepaldi et al. (2010), it is more difficult to interpret the neurophysiological data in relation to these predictions.

The experiment reported in this article seeks to revisit the predictions put forward in the theory of Crepaldi et al. (2010), by comparing masked priming effects observed for regular (e.g. asks-ASK) and irregular (e.g. seen-SEE) English inflections while recording ERPs. Critically, we improved on previous studies in several ways: (a) by using an SOA more typical of masked morphological priming experiments (40 ms); (b) by achieving superior stimulus matching around prime length and prime-target overlap across conditions; and (c) by increasing our power to detect differences between irregular and regular inflections. We sought to achieve superior stimulus matching across regular and irregular inflectional conditions primarily by using the regular third-person singular tense (e.g. stirs-STIR) as opposed to the regular past tense (e.g. stirred-STIR); primes of the former type are far easier to match to the irregular past tense on length and prime-target overlap than primes of the latter type.[2] We sought to achieve greater power than in previous studies both by increasing the number of participants (60% increase on Morris & Stockall, 2012; 100% increase on Fruchter et al., 2013), and by using a temporal Principal Components Analysis which achieves a more optimal un-mixing of ERP components than the averaging of ERP amplitudes in pre-defined time-ranges ('time windows'). On the theory put forward by Crepaldi et al. (2010), we expect greater masked priming effects for English regular than irregular inflections, and for masked priming effects for the regular inflections to emerge earlier in the ERP segment than those for the irregular inflections.

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[2] The use of third-person singular tense as opposed to regular past tense means that while there is a tense shift in the irregular prime-target pairs (e.g. fell-FALL), primes and targets in the regular condition are both in the present tense. However, we know of no evidence that this factor would be relevant to masked priming effects on lexical decision.

Method

Participants

Thirty two Exeter University students (21 female, 11 male; mean age, 24, SD, 7.9) were given course credits or paid £8 for their participation in the experiment.

Stimuli

180 English monomorphemic words were selected as targets and distributed evenly between two conditions. In the regular condition, targets were paired with a regular, third-person singular inflected form to serve as a related prime (e.g., *wrap* was paired with *wraps*, *stir* with *stirs,* and so on), whereas in the irregular condition they were paired with an irregularly inflected past-tense form (e.g., *wear* was paired with *wore*, *bend* with *bent*, and so on). Target words were matched as closely as possible across conditions for length in letters (4.41 ± .76 for the regular condition vs. 4.42 ± .76 for the irregular condition), log-transformed CELEX written frequency (2.47 ± .60 vs. 2.90 ± .67; Baayen, Piepenbrock, & van Rijn, 1993), number of syllables (1.01 ± .11 vs. 1.01 ± .11), number of phonemes (3.43 ± .75 vs. 3.46 ± .74), mean log bigram frequency (2.59 ± .42 vs. 3.01 ± .39), and orthographic neighbourhood size (3.96 ± 3.47 vs. 7.87 ± 4.68). For each target word, an unrelated control prime was selected that matched the related prime on its orthographic structure (e.g. *wraps-WRAP* was compared to *yolks-WRAP* in the regular condition; *bore-BEAR* was compared to *kiss-BEAR* in the irregular condition). Related and control primes were matched closely for length in letters, log-transformed written frequency, log-transformed spoken frequency, number of syllables, number of phonemes, mean log bigram frequency, and orthographic neighbourhood size (see Table 1). In addition, we controlled orthographic overlap, as computed through the MatchCalc application (Davis, 2005), between prime and target across conditions. The complete list of the stimuli is provided in Appendix A.

-- Table 1 about here –

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The stimulus set also included 180 legal nonwords created through the ARC nonword database (Rastle, Harrington, & Coltheart, 2002). These nonwords were comparable to the word targets for length in letters (nonwords: $4.35 \pm .84$; words: $4.42 \pm .76$) and orthographic neighbourhood size (5.21 ± 4.77 vs. 5.91 ± 4.55). They were paired with a new set of word primes that was similar to the set of primes used in the word trials for length in letters (nonword-trial primes: $4.88 \pm .92$; word-trial primes: $4.93 \pm .96$), log-transformed written frequency ($2.29 \pm .76$ vs. $2.36 \pm .82$), log-transformed spoken frequency ($.93 \pm .77$ vs. $.97 \pm .78$), and orthographic neighbourhood size (5.87 ± 4.93 vs. 5.09 ± 4.46). To mirror the structure of the word trials, half of the primes were orthographically similar to the nonword targets, whereas half were not.

The assignment of word targets to the two relatedness conditions was counterbalanced across participants, so that participants received primes from each condition, but saw each target only once. This was achieved by creating two experimental lists, each of which was submitted to half of the participants.

Procedure

The experiment was run in E-Prime 1.1 (Psychology Software Tools, Sharpsburg, PA) using a PC and a 17'' CRT monitor. Each trial started with the presentation of a pattern mask ("#######") presented in 18 point bold style Times New Roman font for 507 ms (38 monitor refreshes at 75 Hz). The mask was followed by the prime presented in 15 point bold style lower case Courier New font for 40 ms (3 monitor refreshes at 75 Hz), after which the target was presented until a response was made. The target was presented in the same font as the prime, but in upper case. The participant sat at ~60 cm from the monitor was asked to press on a standard 'qwerty' keyboard the 'm' key if the target stimulus was a word and the 'c' key if it was not a word. The testing session started with a short block of 24 practice trials and continued with 360 experimental trials in 6 blocks of 60 trials each; the order of conditions was randomised.

EEG/ERPs

The EEG was acquired using 64 Ag/AgCl active electrodes embedded as a 10-10 configuration

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(see Figure 2D) into an elastic cap and two 32-channel amplifiers (BrainProducts, Munich, Germany) with a bandpass of 0.016-100 Hz, a sampling rate of 500 Hz, the on-line reference electrode at Cz and ground electrode at AFz; the impedance in all electrodes was kept below 10 kΩ. Off-line, the EEG was low-pass filtered (20 Hz; 48 dB/octave) and re-referenced to the average of the two earlobe electrodes. The EEG was corrected for eye-blink and eye-movement artefacts using Independent Component Analysis (Infomax ICA, Bell & Sejnovski, 1995, implemented in Vision Analyzer, BrainProducts, Munich, Germany); previous work in our laboratory has documented the benefits of ICA in ERP analysis (Lavric, Bregadze & Benattayallah, 2010). The independent components extracted by ICA from every participant's EEG were inspected and those with characteristic eye-blink and eye-movement topographies were subtracted from the EEG. The resulting EEG was segmented into 590-ms long segments time-locked to the prime onset (thus resulting in 550 ms of EEG following target presentation) plus a 100 ms pre-prime baseline. The segments were baseline-corrected, inspected for residual muscle and head movement artifact (and those containing such artifact discarded) and averaged for each participant and condition.

In order to analyse the amplitude throughout the whole ERP segment without setting arbitrary time-windows, we used temporal Principal Components Analysis (PCA, Donchin & Hefley, 1978), which we have used previously in the ERP-language domain (Weber & Lavric, 2008). Temporal PCA reduces the time-course of the ERP to several temporal principal components (eigenvectors) – these can be seen as 'virtual time-windows' (see Appendix B1 for further details). The ERP amplitude for each of these 'virtual time-windows' is analysed statistically by examining component *scores*, which specify the amplitude of a given PCA component for each case (electrode/condition/subject). In our experiment, the scores of PCA components that explained at least 2% of the variance of the ERP amplitude over the entire segment were submitted to ANOVA with factors prime, regularity, region, and laterality. Spatial factors region and laterality were constructed by averaging groups of electrodes. Factor region comprised four anterior-to-posterior scalp regions, and factor laterality comprised three levels within each region (left, midline, right;

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see Figure 3C).

Results

Behavioural results

Two items were removed from the behavioural and ERP analyses due to high error rates: *trot* (regular condition; 34% errors), and *wring* (irregular condition; 38% errors). RTs were shorter for targets preceded by related primes, both by participants, $F_1(1.31) = 26.58$; $p < .001$, and by items, $F_2(1,176) = 41.15$, $p < .001$. Although this priming effect was statistically greater for the regular condition (related, 651 ms; unrelated, 687 ms; priming effect 36 ms), relative to the irregular condition (related, 639 ms; unrelated, 657 ms; priming effect 18 ms), $F_1(1.31) = 5.83$; $p < .05$; $F_2(1,176) = 4.06$, $p < .05$, it was significant for both the regulars, $t_1(31) = 5.99$, $p < .001$, $t_2(89) = 5.59$, $p < .001$, and the irregulars, $t_1(31) = 2.73$, $p < .001$, $t_2(89) = 3.31$, $p = .001$. There was also a main effect of regularity, $F_1(1.31) = 15.96$; $p < .001$; $F_2(1,176) = 11.38$, $p = .001$, with longer RTs for irregular targets (669 ms) than for the regular targets (648 ms). Although the error rates were lower for the targets preceded by related primes (2.6 %) than for those preceded by unrelated primes (3.1%), this effect did not approach statistical significance and neither did the interaction between priming and regularity. The main effect of regularity was reliable, $F_1(1.31) = 9.16$; $p = .005$; $F_2(1,176) = 5.76$, $p = .017$, reflecting a lower error rate for irregular targets (2.1%) than for the regular targets (3.6%).

ERP results

Figure 2 shows the ERP waveforms in a selection of electrodes as a function of regularity and prime relatedness. This figure reveals clear differences between the ERPs to targets preceded by unrelated versus related primes in the regular condition. These differences are particularly large at approximately 400 ms after the onset of the target (reflecting the attenuation of the N400 potential), but they are also present earlier (e.g. in the left frontal electrodes). Some effects of prime relatedness (though noticeably smaller) are also present in the irregular condition. Figure 3A shows how the above (unrelated-related) differences are distributed over the entire scalp, and how the

topography of these priming effects evolves over time (in 50 ms intervals) for the regular and irregular conditions. Figure 3B illustrates the results of the temporal PCA. Line plots show the time-courses of PCA components; maps show the effect of priming (the unrelated-related difference) in the principal components that were sensitive to priming as determined through ANOVA (see below).

-- Figure 2 about here --

The earliest component that was affected by priming was principal component 1 (PC1), which explained 10% of the entire ERP variance. This component was relatively protracted, explaining most of the ERP variance up to ~180 ms following prime onset, as well as substantial variance at ~200-250 ms. ANOVA on its scores revealed a reliable interaction between prime, regularity, region, and laterality, $F(6,180) = 3.63$, $p = .007$, indicating the fact that the effects of priming were not equivalent for the regular and irregular conditions. Follow-up separate ANOVAs for regular and irregular items revealed a significant interaction between prime, region, and laterality for the regular condition, $F(6,180) = 3.96$, $p = .002$. There were no significant effects involving prime for the irregular items (all $Fs<1.3$). Although we did not have an *a-priori* expectation with regard to the scalp distribution of the priming effect in the regular condition, the topographic maps of PC1 show a negative-polarity modulation of brain potentials by unrelated primes relative to related primes over the left frontal and right posterior scalp (Figure 3B). Based on this prime x region x laterality interaction, we ran three follow-up prime x region ANOVAs for the regular condition, one for each level of laterality. However, no significant interactions between prime and region emerged ($Fs<1.4$) in any of these tests. Thus, the significant interaction between prime and the topographic factors (region and laterality) indicates that prime relatedness modulates the spatial distribution of activity in the cortex for the regular condition, but it is not clear as to where on the scalp this modulation is reliable.

The finding that PC1 was modulated by priming only in the regular condition, with such a modulation apparently absent for the irregulars, suggests a processing stage in which only regularly

inflected words are sensitive to priming. This conclusion rests largely on the *absence* of a priming

effect in the irregular condition, but conventional statistics cannot assess the likelihood of an effect

being absent. We therefore turned to a Bayesian statistical test proposed by Masson (2011), which

we have used previously in ERP research on derivational morphology (Lavric et al., 2012; see

Appendix B2 for further details). We started with the interaction that was significant in the regular

condition: prime by region by laterality, and computed the probability (*posterior probability* in

Bayesian terms) that it was absent for the irregulars (the posterior probability of the null hypothesis,

H_0). This analysis yielded a posterior probability of the null of .998. According to Raftery's (1995)

classification of evidence based on posterior probability into *weak* (.5–.75), *positive* (.75–.95),

strong (.95–.99) and *very strong* (>.99), this analysis provided *very strong* evidence for the absence

of this interaction in the irregular condition. The posterior probabilities for the prime by region by

laterality interaction in the regular condition were .18 for the null hypothesis and .82 for H_1,

providing *positive* evidence for the presence of an interaction effect (and weak evidence for its

absence) – an outcome consistent with the classic ANOVA test above. To rule out other non-null

effects of priming in the irregular condition, we also applied the Bayesian test to the main effect of

prime, as well as the prime x region, and prime x laterality interactions. The posterior probabilities

for H_0 were .83, .998 and .95, respectively, providing *positive* to *very strong* evidence for the

absence of any effect of priming on this principal component in the irregular condition.

In temporal order, the next principal component to show sensitivity to priming was

component 4 (PC4), which was most prominent in the 300-400 ms range, and explained 18% of the

total ERP variance. ANOVA for this component revealed a reliable interaction between prime and

region, $F(3,90) = 9.78$, $p = .001$, reflecting a positive-polarity modulation of brain potentials by

unrelated primes relative to related primes over the posterior scalp, accompanied by a negative-

polarity modulation over the anterior scalp. Although this priming effect did not interact

significantly with regularity ($F<1$), in the interest of documenting the topography of masked-

priming effects, we conducted Bonferroni-corrected t-tests for all regions of the scalp. No t-test

survived correction, the nearest being the test for the left occipital region (Figure 3C), t(31)=2.8, p(uncor)=.009.

The last component to be sensitive to priming was principal component 5 (PC5), which captured the variance in the N400 time range (400-600 ms following prime onset), and explained 29% of the total ERP variance. ANOVA for this component revealed a main effect of prime, $F(1,30) = 20.04$, $p < .001$, as well as a prime by region interaction, $F(3,90) = 12.1$, $p < .001$, and a prime by regularity interaction, $F(1,30) = 4.2$, $p < .05$. The interaction between prime and region was indicative of a robust attenuation of the large negative-polarity ERP peak (N400) for related primes relative to unrelated primes over the posterior scalp (see Figure 2 and Figure 3A and B). The interaction between prime and regularity indicated that this N400 reduction by related primes was larger in the regular condition than in the irregular condition. In order to investigate this prime by regularity interaction further, we conducted separate ANOVAs for the regular and irregular conditions. For the regular condition, these follow-up tests revealed a main effect of prime, $F(1,30) = 24.3$, $p < .001$, and prime by region interaction, $F(3,90) = 10.8$, $p = .001$. Follow-up Bonferroni-corrected t-tests by region in the regular condition were significant for all the regions but one (frontal anterior right), with significant t(31) values ranging from 3.42 to 5.8 and (corrected) p values from .024 to .00003. For the irregular condition, though numerically much smaller, the N400 attenuation in the related prime condition was nevertheless statistically significant, as indicated by a prime by region interaction, $F(3,90) = 5.11$, $p=.015$. The main effect of prime failed to reach significance in this condition, $F(1,30) = 2.82$, $p = .1$, and so did the t-tests by region (largest t(31) = 2.1, p(uncor) =.041 in the left parietal region), further emphasising how feeble the modulation of N400 by priming was for the irregulars, relative to the regulars.

We also examined whether regularity had an effect on the onset of the N400 priming effect. Since N400 is believed to reflect a cumulative influence arising at multiple stages of processing, an earlier processing locus of priming for the regulars should be reflected in a substantially earlier onset of the N400 priming effect in this condition. To test this prediction, we computed (separately

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for the regulars and irregulars) the unrelated-minus-related ERP difference averaged over all EEG electrodes – the Global Field Power (GFP; Appendix B.3 contains further details of this analysis). This computation reveals a clear 'bump' corresponding to the N400 attenuation by related primes (see Figure 3D; note that GFP calculation involves squaring the values at each electrode, hence the negative-polarity unrelated-related difference in the raw ERPs becomes positively-signed in the GFP plot). We took the 'dip' immediately preceding the N400 effect as its onset and estimated its latency (see Appendix B.3): it was 48 ± 2 ms earlier in the regular condition than in the irregular condition, a difference that was highly significant, $t(31) = 23.92$, $p < .001$.

General Discussion

The predictions derived from Crepaldi et al.'s (2010) theory of the recognition of morphologically-complex words were fully supported. Significant behavioural masked priming effects were observed for both regular and irregular inflections, but were significantly greater for regular inflections. These data are also consistent with the behavioural masked priming effects reported by Morris and Stockall (2012) and Fruchter et al. (2013). Perhaps more importantly, ERP analyses revealed for the first time different time courses for masked regular and irregular inflectional priming. Significant priming for regular but not irregular inflections emerged in the first temporal PCA window of the ERP (reflecting processing up to 250 ms post target onset). Further, while significant priming for both regular and irregular inflections was observed in the range of the N400 potential (captured by the final temporal PCA window reflecting processing ~400-600 ms post target onset), the N400 modulation by priming had a substantially earlier onset and greater magnitude for the regular inflections.

Before considering the theoretical implications of these results, we must address the important question of whether the priming effects observed here reflect morphological similarity as opposed to orthographic similarity. Indeed, a potential weakness of our study is that we measured morphological priming against an *unrelated* baseline as opposed to an *orthographic* baseline that controls pure letter overlap across related primes and targets. However, previous behavioural and

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ERP research has shown repeatedly that masked morphological priming effects (whether derivational or inflectional) cannot be reduced to orthographic priming effects. Indeed, in studies in which word primes are used (as is the case here), orthographic priming effects are typically non-significant or even inhibitory, as opposed to the strong facilitation observed in the case of morphological primes. Rastle and Davis (2008) reviewed 14 studies that assessed masked morphological priming against an orthographic baseline; these studies yielded an average masked morphological priming effect of 30ms and an average masked orthographic priming effect of 2ms (see also e.g. Crepaldi et al., Lavric et al., 2007, 2011; Longtin et al., 2003; McCormick et al., 2008; Rastle et al., 2004). This pattern is also true in ERP measures of masked priming, where morphological priming is reliably distinguished from orthographic priming (Lavric et al., 2007). Further, if the priming effects observed here reflected simple letter overlap, then we would expect to see some relationship between priming and degree of letter overlap. This prediction is easily tested in the irregular condition (where there is sufficient variability in the amount of orthographic overlap across prime-target pairs); this analysis shows no relationship between the degree of letter overlap and priming (r-squared=0.01). Based on this analysis and the substantial body of previous literature showing that masked morphological priming effects cannot be reduced to orthographic effects, we are confident in asserting that the priming effects observed in our study are the result of morphological overlap between primes and targets.

The behavioural and ERP results observed in this study offer strong support to the model described by Crepaldi et al. (2010), in which English regular and irregular inflections overlap their stems at lexical-semantic levels of representation, while only regular inflections overlap their stems at the initial morpho-orthographic level of representation. The fact that regular inflections overlap their stems at two levels of representation while irregular inflections overlap their stems at only one level of representation explains our observation of larger masked priming effects for regular inflections than irregular inflections. Further, the fact that regular inflections but not irregular inflections overlap their stems at the early morpho-orthographic level of processing explains our

observation that regulars but not irregulars showed ERP priming in the earliest PCA window identified. These two differences in the nature of representation between regulars and irregulars together explain our observations that regulars displayed N400 priming of a greater magnitude and earlier onset than irregulars.

The 'form-then-meaning' time-course revealed in this study is consistent with the temporal characterisation of the recognition of printed *derived* forms uncovered in previous research (e.g. Crepaldi et al., 2010; Lavric et al., 2007, 2012; Rastle et al., 2004). Further, this study adds to a remarkably consistent picture of the precise timing of the proposed morpho-orthographic segmentation process. Previous ERP (Lavric et al., 2012) and MEG (Lewis, Solomyak, & Marantz, 2011; Solomyak & Marantz, 2010) studies have converged on a time-course around 170-190ms post target onset, while PC1 in this study explained most of the variance in the ERP up to 200ms post target onset. While these data support a hierarchical 'form-then-meaning' theory of morphological processing, they argue against theories of morphological processing that propose a much tighter coupling between orthographic and semantic processing. One such theory claims that visual word recognition involves "near simultaneous access to the ortho-phonological and semantic properties of words" (Feldman, O'Connor, & Moscoso del Prado Martín, 2009, p.684). Another such theory argues that word recognition is based on two parallel pathways, one of which involves rapid access to semantic information on the basis of a coarse-grained orthographic representation, and the other of which involves fine-grained orthographic processing including morphological decomposition (Diependaele, Sandra, & Grainger, 2005; Diependaele, Sandra, & Grainger, 2009; Diependaele, Duñabeitia, Morris, & Keuleers, 2011; Grainger & Ziegler, 2011). Though these theories have not been applied to the problem of inflectional morphology, the broad proposal that morpho-orthographic and semantic levels of analysis arise either simultaneously or in parallel is inconsistent with the ERP data arising from this study, which reveals *virtually no overlap at all* in the time windows ascribed to morpho-orthographic and lexical-semantic processing (PC1 versus PC5).

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In addition to offering support for a hierarchical 'form-then-meaning' theory of visual word recognition, this work helps to reconcile previous research on inflectional and derivational processing, which have tended to be treated within different lines of inquiry. In particular, research on the processing of inflectional morphology has been dominated by a heated debate over whether irregular forms are processed by a qualitatively different mechanism from regular forms (e.g. Pinker, 1991; Pinker & Prince, 1988) or whether a single mechanism can handle both regular and irregular forms (e.g. Rumelhart & McClelland, 1986; Joanisse & Seidenberg, 1999). Our findings demonstrate that the processing of regular and irregular inflectional forms can be understood within a theory of the recognition of printed words that was developed largely though the investigation of derivational processing. These findings reveal important differences between regular and irregular inflectional forms that have psychological consequences; specifically, regular forms can be parsed on a morpho-orthographic basis into their components while irregular forms cannot. However, despite this important difference between regular and irregular inflections at the morpho-orthographic level of representation, we reject any assertion that our data support a 'words and rules' framework (e.g. Pinker, 1991; Pinker & Prince, 1988), in which regular and irregular forms would require processing along two qualitatively different 'routes' for recognition. Indeed, such accounts would seem to predict that masked priming effects should not have emerged at all for irregular inflections. This prediction is clearly not supported.

While we reject a 'word and rules' framework for understanding these data, we also believe that our findings pose some challenges for distributed-connectionist approaches to understanding word recognition. Modellers from this perspective assert that morphological effects arise as a consequence of the convergence of orthographic, phonological, and semantic relatedness characteristic of derivationally- and inflectionally-complex words and their stems (Kielar & Joanisse, 2009; Plaut & Gonnerman, 2000). On this perspective, because irregular forms participate to varying degrees in this systematicity (e.g. orthographic / phonological regularities still exist in irregular forms, as in kept-keep, slept-sleep, wept-weep), there is no sharp distinction between

regular and irregular inflections. Thus, these models are well suited to explain (a) our observation of significant masked priming effects for irregular inflections (both behaviourally and electrophysiologically in the N400 window) and (b) our observation of larger masked priming effects for regular inflections than for irregular inflections (again, both behaviourally and electrophysiologically in the N400 window). Indeed, these findings are consistent with those reported by Kielar and Joanisse (2009), who observed graded effects of inflectional regularity on the N400 in the context of both cross-modal priming and visual priming with fully-visible primes, and as such argued in favour of a distributed-connectionist model. However, we find it more difficult to conceive how current implementations would account for the observation of robust priming effects for regular inflections in the absence of priming effects for irregular inflections in the earliest time window studied. These models have tended to focus on morphological effects arising as a function of learned hidden unit representations that express regularities across the mapping between orthography and meaning (e.g. Plaut & Gonnerman, 2000). One possibility, given the highly systematic formal overlap between regular inflections and their stems, is that the early effect of inflectional regularity that we observed could be captured within these models in the distributed representations of orthography itself (see Rastle & Davis, 2008 for discussion and possible implementations). However, evaluating this potential solution would clearly require the development of realistic, learned orthographic representations in this class of model.

Most generally, our data suggest that the recognition of regular and irregular inflectional forms is characterised by a hierarchical theory in which the processing of formal aspects of a stimulus is followed by the processing of its semantic aspects. This 'form-then-meaning' time-course is consistent with the temporal characterisation of the recognition of printed derived forms uncovered in previous research (e.g. Crepaldi et al., 2010; Lavric et al., 2007, 2012; Rastle et al., 2004). We believe that these data support the particular theory developed by Crepaldi et al. (2010), which is based on the classical localist modelling tradition exemplified in work on speech production (e.g. Levelt, Roelofs, & Meyer, 1999; Roelofs, 1992) and visual word recognition (e.g. Coltheart et al.,

2001). However, we believe that further exploration of distributed-connectionist approaches to understanding morphological processing may also prove fruitful in formulating a fully-implemented temporal characterisation of the recognition of inflectionally- and derivationally-complex printed words.

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Appendix A

Appendix A. Target and prime words used in the experiment.

Target	Related prime	Control prime
Regular condition		
ADD	adds	cups
ASK	asks	ends
BOMB	bombs	halls
BRUISE	bruises	maggots
CARVE	carves	blinks
CAUSE	causes	limits
CHARGE	charges	windows
CHEER	cheers	weighs
CHEW	chews	trams
CHOKE	chokes	trills
CHOP	chops	mains
CLIP	clips	hunts
COIL	coils	beers
COMB	combs	hives
CRAWL	crawls	taunts
CURL	curls	moons
CURVE	curves	stamps
DANCE	dances	pilots
DRIP	drips	jowls
DROP	drops	twins
DRUM	drums	kills

FENCE	fences	admits
FILM	films	tends
FIT	fits	mars
FLOAT	floats	nymphs
FLOOD	floods	spears
FRAME	frames	sweets
GLOW	glows	curds
GLUE	glues	dawns
GRAB	grabs	spuds
GRIN	grins	dales
GROAN	groans	twists
GUIDE	guides	stalls
HAUNT	haunts	probes
JOIN	joins	watts
JOKE	jokes	lists
JUDGE	judges	allows
KNOCK	knocks	plumes
KNOT	knots	bulls
LEARN	learns	themes
LIE	lies	wars
MOAN	moans	jerks
MOOR	moors	aides
NOD	nods	tags
PAUSE	pauses	minors
PHONE	phones	tracts

PLAN	plans	birds
PLAY	plays	views
PLUG	plugs	baths
PRAY	prays	colts
REIGN	reigns	cloaks
RHYME	rhymes	splits
RISK	risks	cells
RULE	rules	costs
SAW	saws	cots
SCREAM	screams	noughts
SCREW	screws	thumbs
SCRUB	scrubs	whelks
SERVE	serves	chiefs
SHRUG	shrugs	heaves
SIGN	signs	yards
SIN	sins	pots
SNIFF	sniffs	trumps
SNOW	snows	mists
SOAK	soaks	brews
SPOIL	spoils	drunks
SPRAY	sprays	cloths
SQUEAK	squeaks	throughs
SQUEAL	squeals	throngs
STAY	stays	chips
STEP	steps	banks

STIR	stirs	heals
STRIP	strips	clerks
SUIT	suits	loves
TEMPT	tempts	cranks
TIE	ties	bags
TREAT	treats	chunks
TRIP	trips	bells
TROT	trots	manes
TYPE	types	calls
USE	uses	ions
WAIL	wails	dents
WALK	walks	stops
WANDER	wanders	commits
WHINE	whines	broods
WHIP	whips	blues
WHIRL	whirls	stoops
WRAP	wraps	yolks
WRECK	wrecks	moulds
YAWN	yawns	chums
Irregular condition		
BEAR	bore	kiss
BEGIN	begun	adult
BEND	bent	tour
BIND	bound	shock

BITE	bit	son
BLEED	bled	crow
BLOW	blew	trap
BREAK	broke	youth
BREED	bred	hull
BRING	brought	strange
BUILD	built	space
BUY	bought	spread
CATCH	caught	friend
CHOOSE	chose	tough
CLING	clung	feast
CREEP	crept	shaft
DIG	dug	arc
DRAW	drew	hole
DRIVE	drove	stock
EAT	ate	cry
FALL	fell	rich
FEED	fed	aim
FEEL	felt	hand
FIGHT	fought	screen
FIND	found	small
FLEE	fled	nick
FLY	flew	grip
FREEZE	froze	guild
GIVE	gave	soon

GROW	grew	camp
HANG	hung	cool
HIDE	hid	rub
HOLD	held	rest
KEEP	kept	road
KNEEL	knelt	dough
KNOW	knew	head
LEAD	led	sun
LEAVE	left	both
LEND	lent	bass
LOSE	lost	hair
MAKE	made	such
MEET	met	law
RIDE	rode	tool
RING	rang	loud
RISE	rose	holy
RUN	ran	sex
SAY	said	been
SEE	seen	mind
SEEK	sought	throat
SELL	sold	hurt
SEND	sent	wall
SHAKE	shook	guilt
SHOOT	shot	lack
SHRINK	shrank	plaque

SING	sang	gaze
SINK	sank	haze
SIT	sat	bed
SLAY	slew	zing
SLEEP	slept	chain
SLIDE	slid	pact
SLING	slung	creed
SPEAK	spoke	court
SPEED	sped	blur
SPEND	spent	mouth
SPIT	spat	maze
SPRING	sprang	blonde
STAND	stood	voice
STEAL	stole	punch
STICK	stuck	rough
STING	stung	flare
STINK	stank	grape
STRIKE	struck	flight
STRING	strung	bleach
SWEAR	swore	thump
SWEEP	swept	climb
SWIM	swam	jeep
SWING	swung	beard
TAKE	took	room
TEACH	taught	ground

TEAR	tore	boom
TELL	told	kind
THINK	thought	stretch
THROW	threw	false
WAKE	woke	inch
WEAR	wore	pool
WEAVE	wove	mush
WEEP	wept	horn
WIN	won	bar
WRING	wrung	plush
WRITE	wrote	glass

Appendix B

B1. Temporal principal components analysis

The PCA was performed in SPSS. We used a standard PCA on the covariance matrix with Varimax rotation (which results in uncorrelated components) and component extraction criterion of eigenvalue ≥1 (the Kaiser criterion). The data matrix submitted to PCA had 295 variables (all the time-points of the 590 ms ERP segment sampled every 2 ms) and 8064 cases (63 electrodes * 4 conditions * 32 participants). Component scores were computed using the regression method.

B2. Bayesian statistical analysis

To estimate the likelihood of the null in key interactions, we employed a Bayesian statistical test proposed by Masson (2011), which uses ANOVA sums of squares and assumes a prior distribution of possible effect size parameter values that is a standard normal distribution centered on the value of the effect size observed in the data and extending over the distribution of observed data (Raftery, 1999), also referred as 'unit information prior'(Kass & Wasserman, 1995). Because the previous behavioural and eletrophysiological evidence did not provide strong reasons to favour either H_0 or H_1, the prior probabilities assumed for both hypotheses were 0.5 ('uninformative priors'). There is no established method for computing the number of observations (n) for this Bayesian test for interactions involving multiple factors with >2 levels (Masson, personal communication). One solution is to reduce our 2 (prime) x 4 (anterior-posterior) x 3 (laterality) interaction to a simpler effect. The inspection of the topographic modulation by priming in the regular condition in the PCA component 1 (in Figure 3B) shows the largest differences in left frontal and right temporal-occipital scalp regions. We therefore removed for the Bayesian test one level of laterality (midline regions), leaving only the left and right scalp regions, thus simplifying our interaction to a 2 x 4 x 2 one. Since now only one factor had >2 levels, the interaction could be reduced to a main effect of that factor, by computing difference scores for the remaining factors. This permitted a straightforward

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computation of n=s(c-1), where s is the number of subjects and c is the number of levels of the 4-level factor (as in Masson, 2011). Note that we ensured that the interactions involving factor prime were still significant after reducing the laterality factor to 2 levels: prime x regularity x region x laterality, $F_{(3, 93)}=4.34$, $p=.015$; prime x region x laterality for in the regular condition, $F_{(3, 93)}=5.88$, $p=.002$.

B3. Analysis of the onset of N400 priming effect

Although we used PCA for the amplitude analysis, PCA is not used for analysing ERP latencies. We therefore computed the unrelated-minus-related ERP difference waves for the regulars and irregulars separately. To circumvent arbitrary selection of electrodes, we calculated the Global Field Power of each difference wave – a measure of differential activity across the entire scalp, computed as *root-mean-square* (the square root of the average over the squared unrelated-minus-related differences in all electrodes). We then used the latency of the GFP minimum immediately preceding the N400 effect as an estimate of the onset of the N400 priming effect (see Figure 2E); to ensure unambiguous identification of this minimum in the GFP, we used the "jackknifing" method (Miller, Patterson & Ulrich, 1998) briefly summarized in what follows. As well as the average difference wave over all the subjects, a further 32 difference waves were computed, each omitting one subject's data. The latency of the minimum preceding the N400 was found for each of these 'sub-averages', the difference between the latencies for regulars and irregulars calculated, and the standard deviation of this difference over the 32 sub-averages computed. From this, an estimate of the variability of the difference in onset over participants could be derived using Miller et al.'s formula for computing the standard error, thus enabling the computation of the t-statistic.

Author Note

Table 1

Table 1. Characteristics of the related and control primes used in the experiment.

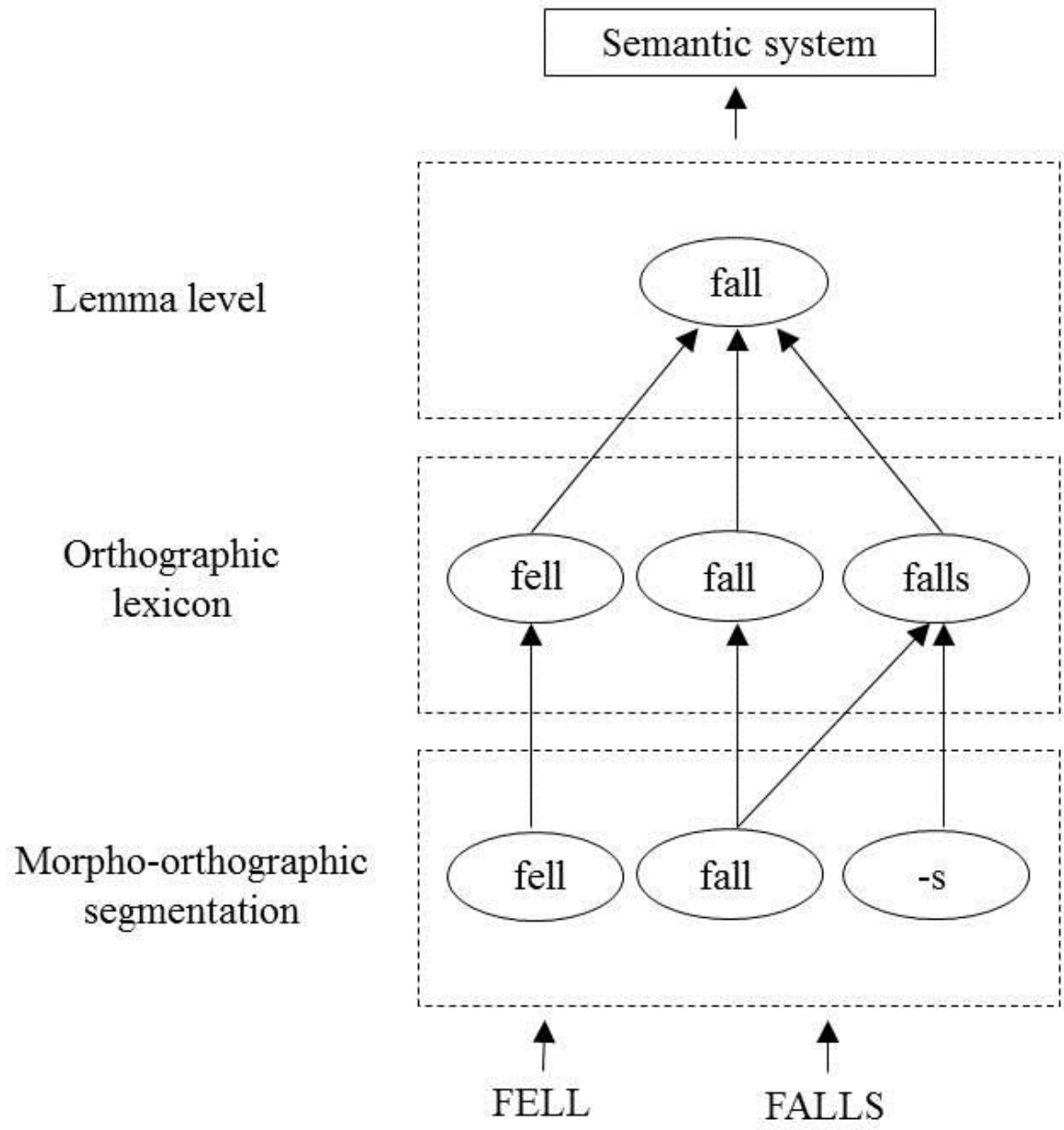|	Regular condition				Irregular condition			
	Related primes		Control primes		Related primes		Control primes	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Letters	5.41	.76	5.41	.76	4.46	.90	4.46	.90
Log WF	1.88	.63	1.85	.61	2.87	.70	2.85	.69
Log SF	.66	.59	.60	.57	1.26	.87	1.32	.83
Syllables	1.09	.32	1.10	.30	1.02	.15	1.02	.15
Phonemes	4.43	.92	4.59	.82	3.62	.70	3.49	.75
MLBF	2.64	.35	2.61	.32	2.90	.40	2.89	.36
N	3.26	2.65	4.37	4.17	7.40	5.05	6.01	4.49
Orth overlap	.84	.02	.05	.07	.72	.14	.01	.06

Note. Log WF, log-transformed written frequency; Log WF, log-transformed spoken frequency; MLBF, mean log bigram frequency; N, orthographic neighbourhood size; Orth overlap, orthographic overlap between primes and targets, computed according to the spatial coding for letter position (Davis, 2010). Frequency values were computed from the CELEX database (Baayen et al., 1993).
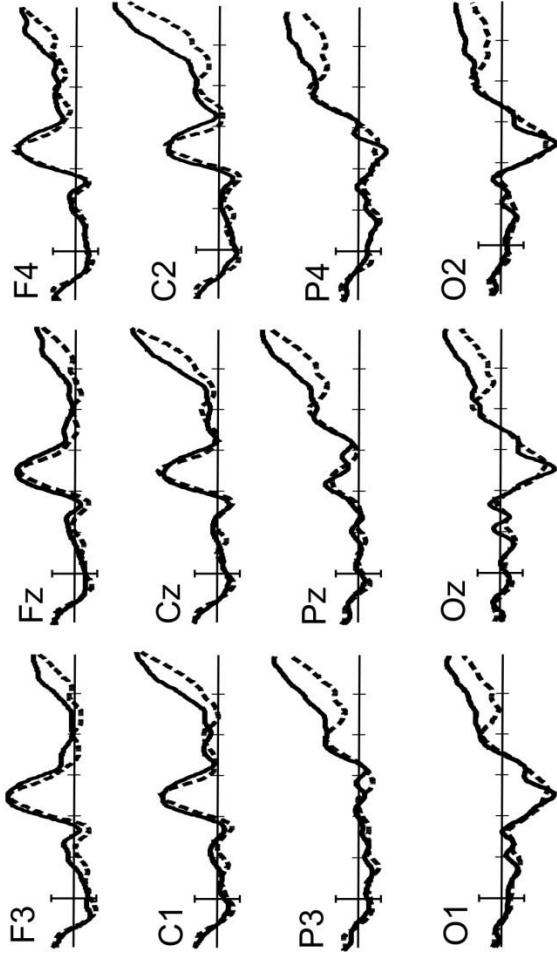
Figure Captions

Figure 1. The model of the recognition of morphologically-complex words proposed by Crepaldi et al. (2010).

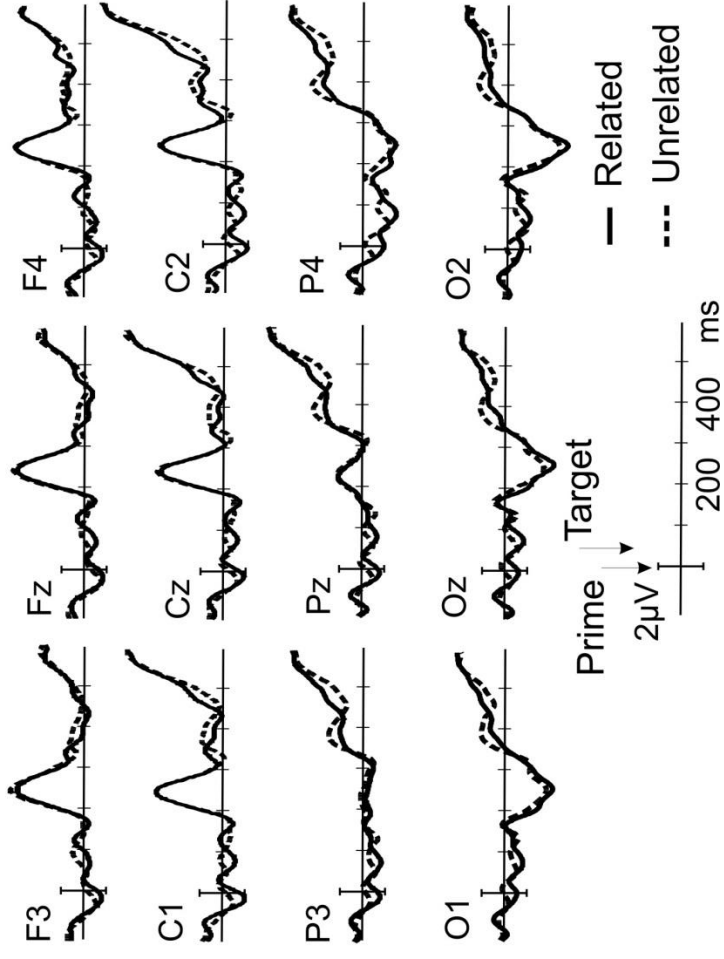Figure 2. ERP waveforms by prime type and regularity.

Figure 3. A. The spline-interpolated scalp distribution (topography) of the priming effect averaged for intervals of 50 ms. B. The time-courses (*loadings*) and topographic maps (*scores*) of the temporal principal components; the maps represent the difference between the scores for the unrelated and related prime conditions (as in A above) for the components that showed significant effects of prime. C. The scalp regions for which the temporal component scores were averaged to yield the factors region (anterior-posterior) and laterality in ANOVA. D. Global Field Power (root-mean-square) of the unrelated-related difference wave in the ERPs; dashed vertical lines show the pre-N400 minima taken as the onset of the N400 priming-induced attenuation.

Semantic system

Lemma level

fall

Orthographic
lexicon

fell   fall   falls

Morpho-orthographic
segmentation

fell   fall   -s

FELL   FALLS

Regular

F3 Fz F4
C1 Cz C2
P3 Pz P4
O1 Oz O2

Irregular

F3 Fz F4
C1 Cz C2
P3 Pz P4
O1 Oz O2

Prime Target
2μV
200 400 ms

—— Related
---- Unrelated

A Topography of priming effect (unrelated minus related)

Reg

Irr

50 ms

-1.2μV   0μV   1.2μV
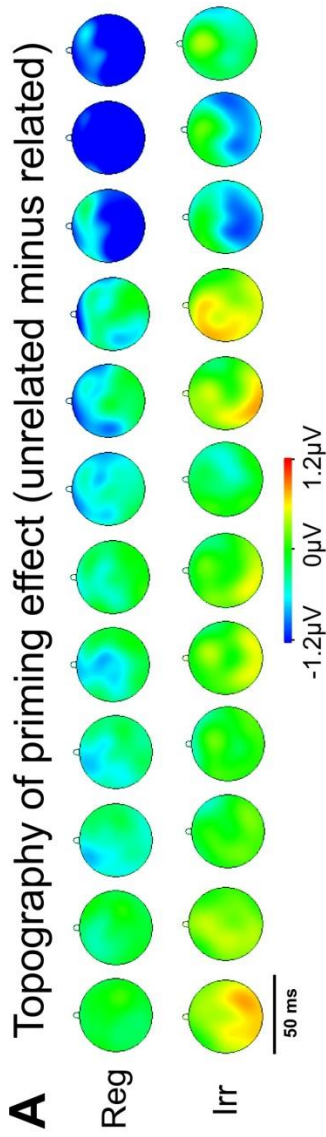
B Temporal PCA: components & topographies of priming effect

Regular

Irregular

No priming

Priming & regularity interact; Priming only detectable for regulars

Priming present and equivalent for regulars and irregulars

Priming & regularity interact; priming present for regulars and irregulars but substantially greater for regulars

Prime   Target

100   200   300   400   500   ms

C Scalp regions

D N400 effect: onset latency

N400 effect

48 ms

Prime Target

GFP

1μV

Unrelated minus related, regular

Unrelated minus related, irregular

Onset of N400 priming effect

100   300   500   ms