Is there a difference between pairs like *theoro/theoria*, *pino/poto*, *fetos/feta*? Only in the long term

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1 Introduction

How do we read morphologically complex words? Research on this issue has provided ample evidence that morphologically complex words are decomposed in visual word recognition (e.g. *darkness* is segmented into {dark-} + {ness}) (see Seidenberg and Gonnerman 2000 for review). Although the process of morphological decomposition in visual word recognition is now widely accepted, the role of semantic and orthographic factors therein is still controversial.

One view holds that morphological decomposition is based on semantic information (e.g. Giraudo and Grainger 2001). For example, Marslen-Wilson, Tyler, Waksler and Older (1994) reported robust cross-modal priming effects for stem-target pairs that were morphologically and semantically related (e.g. *hunter/hunt*) but not for pairs that were not semantically related (*department/depart*) (henceforth referred to as "semantically opaque"). This finding led the authors to suggest that decomposition is only applied to morphologically complex words that are related in meaning to their stems, i.e., they are semantically transparent. Contrary to this prediction, under masked priming conditions robust priming can be observed for semantically transparent and semantically opaque morphological relatives (Rastle, Davis and New 2004). These results have lent support to the morpho-orthographic view on segmentation, which holds that morphological decomposition is guided by orthographic information.

Interestingly, this process applies even when the orthographic overlap between the morphological relatives is partial, as in the semantically transparent pairs *adorable/adore*, *metallic/metal* or in the semantically opaque pair *fetish/fete* (McCormick, Rastle and Davis 2008). This finding suggests that the process of morpho-orthographic segmentation is insensitive to regular orthographic alterations found in complex words as well as to their semantic characteristics. In contrast, however, a masked priming study in Greek inflectional morphology comparing priming for high- vs. low-overlap pairs reported priming only for the high-overlap pairs at an SOA of 33 ms. At the 50 ms SOA both conditions showed equivalent priming (Voga and Grainger 2004). Conversely, Tsapkini, Jarema, and Kehayia (2002) compared priming for regular and irregular inflected Greek words matched for orthographic overlap (50%) and found equivalent priming for all types at the short SOA (35 ms), although the form overlap in this study was similar to the low overlap condition (46%) of the Voga and Grainger (2004) study. At the longer SOA (150 ms) Tsapkini *et al*. (2002) reported more priming for regular than for irregular verbs.

Such discrepancies indicate that it is unclear whether morpho-orthographic segmentation can still proceed in the presence of more disruptive orthographic changes (e.g. *abundant/abound,* henceforth referred to as "orthographic opacity") found in morphologically complex words. This is one of the key questions we sought to answer in the experiments reported in this paper. The aforementioned studies with Greek materials highlight the potential for Greek data to be informative regarding the role of extreme orthographic changes in the context of solid morphological relationships. However, these studies focus on inflectional morphology, where priming despite extreme orthographic changes can be due to either increased amount of semantic overlap for inflectional variants, or because orthographic irregularities are more systematic in inflectional morphology than in derivational morphology. In either case, this motivates further experiments to explore the impact of orthographic and semantic transparency in derivation, where these two factors can be independently varied, as we have sought to do in the experiments reported in this paper.

The dissimilarity of masked and delayed priming in the effects of semantic transparency led to the proposal of two processing stages in visual word recognition: an early morpho-orthographic stage, possibly reflected in masked priming, and a later occurring morpho-semantic stage, reflected in delayed priming effects (Rastle and Davis 2008). The experiments presented in this paper explore an important consequence of this proposal, namely that if masked priming reflects orthographic levels of processing, then it should be disrupted when the orthographic overlap between prime and target is diminished, while delayed priming will be more robust to orthographic opacity. To our knowledge this prediction has not been investigated in a single study. Thus, we compare priming effects for semantically transparent and opaque morphological relatives under masked (Experiment 1) and delayed priming conditions (Experiment 2). Further, we explore the sensitivity of masked and delayed priming to more extensive orthographic changes than the ones tested by McCormick *et al*. (2008) (e.g. duplicated consonant, missing 'e'). To this end, we use Greek morphologically complex words. Greek is a morphologically rich language, in which morphophonological rules produce morphologically related but orthographically dissimilar words.

Since Greek has been described as a stem-based language (Ralli 1988) throughout this paper we use the term orthographic opacity/transparency to refer specifically to whether the stem has undergone orthographic changes, i.e., whether prime and target share (or not) the same stem at the level of orthography. Likewise, semantic transparency refers to whether the prime and the target share the same stem at the level of meaning. Sharing meaning is the conventional definition of morphological relationships. In a similar vein, experimental conditions are described in terms of the morpho-semantic (-S/M and +S/M) and orthographic (-O/+O) characteristics of the stem of the prime and the target. The conditions are as follows:

(1) Our first condition contains word pairs that share an orthographically and semantically transparent stem (e.g. θεωρία/θεωρώ , *theoria/theoro*, ‘‘theory/I theorize’’). In this condition the prime and target can be decomposed into stem and suffix, they are morphologically related and they share the same stem (theor-) at the level of meaning and orthography. We refer to this as the +Stem Meaning, +Stem Orthography condition (+S/M, +O).

(2) The second condition is the -Stem meaning, +Stem Orthography condition (-S/M, +O) with semantically opaque and orthographically transparent primes (e.g. μανία/μάνα, *mania/mana*, ‘‘mania/ mother’’). The prime and the target can be decomposed into stem and suffix, they are not morphologically related, and they have orthographically similar stems, which are not related in meaning (*mani*- and *man*-, but the root is the same *man*-. Note that because the suffix -*ia* is very productive in modern Greek, both words could be decomposed synchronically as man-a and man-ia).

(3) The third condition is (to our knowledge) unique to the present study and contains orthographically opaque and semantically transparent pairs (e.g. ποτό/πίνω, *poto/pino,* ‘‘drink/I drink’’). Here, the prime and the target can be decomposed into stem and suffix, they are morphologically related but they have orthographically dissimilar stems (*pin*-, *pot*-), which are nonetheless highly related in meaning. This situation is different to the majority of orthographic changes observed in English derivational morphology (e.g. *adorable/adore*), where the orthographic changes do not allow a perfect parse of the word into complete morphemic units (e.g. removing the suffix *–able* from adorable leaves the nonstem *ador* instead of the stem *adore*). This is the +Stem meaning, -Stem orthography condition (+S/M, -O).

(4) The fourth condition consisted of semantically and orthographically opaque primes (e.g. τρίχα/τρίβω, *tricha/trivo*, ‘‘hair/I rub’’). Although the prime and the target can be decomposed into stem and suffix, they are not morphologically related and they have orthographically dissimilar stems (trich-, triv-), which are not related in meaning. This is the -Stem meaning, -Stem orthography condition (-S/M, -O).

2 Experiment 1: Masked priming

2.1 Method

2.1.1 Participants

47 native Greek speakers between the ages of 18 and 40 years took part. Testing was conducted in Athens, Greece.

2.1.2 Materials

The stimulus set consisted of 192 prime-target pairs, 48 in each of the four conditions (see Orfanidou, Davis and Marslen-Wilson, in press for more details). For each target in the 192 prime/target pairs we selected an unrelated control prime of the same length. 64 unrelated filler word/word pairs and 256 unrelated filler word/pseudoword pairs were added in order to reduce the proportion of related trials to 19% and to balance the number of ‘‘Yes’’ and ‘‘No’’ responses in the experiment. The stimulus set was divided into two lists, with half of the targets in each list preceded by related primes and half by unrelated control primes. Each participant was assigned to one of the two lists and was thus presented with each of the 192 targets only once, either with a related or an unrelated prime, but participated in all priming conditions and saw all the 66 filler unrelated word/word pairs and the 256 filler word/pseudoword pairs, which appeared in the same position in both lists.

For each trial, a forward mask consisting of a row of twelve hash marks (#) was presented in the middle of the screen for 500 ms, followed immediately by the prime displayed for 42 ms, and then immediately masked by the target that remained on the screen for 1000 ms. The participant's task was to make a lexical decision (514 trials) to the target using a four-button response device, in which only the two buttons were relevant for the experiment. The presence of the prime was not mentioned.

2.2 Results and Discussion

Mean reaction times (RTs) and error rates (ERs) were calculated for each participant and each item in each condition. All incorrect responses were discarded from the RT analyses and were treated in separate analysis of the error rates. The error rates were very low overall and the analyses both by participants and by items did not show any significant effects and so these analyses are not reported. Analyses of variance by participants ($F1$) and items ($F2$) were performed on inverse transformed data to reduce the influence of outliers (Ratcliff, 1993). See Table 1 for RTs and error rates for this experiment. In the participants analysis Prime (2 levels), Semantics (2 levels, +Semantics/-Semantics) and Orthography (2 levels, +Orthography/-Orthography) were entered as repeated factors. Version (2 levels) was entered as unrepeated factor. In the items analysis Prime was entered as a repeated factor and Semantics, Orthography, and Version were entered as unrepeated factors.

The ANOVAs revealed a significant interaction between Prime and Orthography ($F1(1,45) = 6.9$, $p = .012$, $F2(1,184) = 6.8$, $p = .010$) and an Orthography by Semantics interaction ($F1(1,45) = 37.8$, $p < .001$, $F2(1,184) = 5.6$, $p = .019$), indicating increased priming for both sets of +O pairs. The interaction between Prime and Semantics did not reach significance ($F1(1,45) 1.6$, $p = .213$, $F2(1,184) = 1.3$, $p = .251$). To establish the source of these interactions, t-tests were performed on individual conditions. There was significant priming in the +S/M, +O condition ($t1(46) = 5.6$, $p < .001$, $t2(47) = 4$, $p < .001$) and the -S/M, +O condition ($t1(46) = 3$, $p = .005$, $t2(47) = 4.1$, $p < .001$). Priming effects in the +S/M, +O condition (28 ms) were numerically larger than priming effects in the -S/M, +O (20 ms) condition, but this difference did not reach statistical significance ($t1(46) = .793$, $p = .432$, $t2(47) = .806$, $p = .406$). In the +S/M, -O condition there was a trend towards the 12 ms priming effect being statistically significant ($t1(46) = 1.9$, $p = .065$, $t2(47) = 2$, $p = .052$), while there was no priming in the -S/M, -O condition ($t1(46)$

=1.5, *p* =.136, *t2*(47) =1.7, *p* =.092). Priming effects did not differ between these two conditions (*t1*(46) =.358, *p* =.722, *t2*(47) =.411, *p* =.683). However, a significant difference was observed between the +S/M, +O and +S/M, -O conditions (*t1*(46) =2.1, *p* =.035, *t2*(47) =1.9, *p* =.052), with larger priming in the +S/M, +O condition than the +S/M, -O condition.

Condition	**+S/M, +O (theoria/theoro)**	**-S/M, +O (mania/mana)**
Related primed	651 (0.01)	686 (0.02)
Control primed	679 (0.01)	706 (0.02)
Priming effect	28	20
	+S/M, -O (poto/pino)	**-S/M, -O (tricha/trivo)**
Related primed	676 (0.02)	670 (0.02)
Control primed	688 (0.03)	678 (0.02)
Priming effect	12	8

Table 1. Mean RTs and Error rates (in parentheses) for Experiment 1.

Consistent with results from English (e.g. Rastle *et al.* 2004) and other languages (e.g. French; Longtin, Segui and Halle 2003, Russian; Russian: Kazanina, Dukova-Zheleva, Geber, Kharlamov and Tonciulescu 2008) masked priming facilitated responses to targets irrespective of whether they were semantically related to their primes (+S, +O) or not (-S, +O). Although there was a hint of priming (12 ms) for the +S, -O pairs this was significantly smaller than the priming for the orthographically transparent, semantically related pairs. Thus, it seems that the robustness to orthographic change in morpho-orthographic decomposition applies for regular orthographic alterations of the type found in English, as in *writer/write* (McCormick *et al.* 2008) but is reduced in the face of more disruptive orthographic changes (see also Voga and Grainger 2004).

3 Experiment 2: delayed priming

3.1 Method

3.1.1 Participants

46 native Greek speakers between the ages of 18 and 40 years took part. Testing was conducted in Athens, Greece.

3.1.2 Stimuli

The experimental pairs were the same as in Experiment 1 (i.e., 192 prime-target pairs, and each prime was also associated with an unrelated control). 192 filler nonword/nonword pairs were added to the stimulus material such that orthographic repetition was not consistently associated with a "yes" lexical decision. The relatedness proportion in this Experiment was 25%. Each trial consisted of the visual presentation of the stimulus, which stayed on the screen for 1000 ms. The inter-trial interval was 1000 ms. Repetitions occurred after approximately 12 intervening items (30 seconds delay between first and second presentation). Participants made 768 lexical decisions. In all other respects the procedure used in this experiment was identical to Experiment 1. (see also Orfanidou *et al.*, in press).

3.2 Results and Discussion

The analysis procedure was the same as in Experiment 1. The ANOVAs revealed a significant interaction between Prime and Semantics (*F1*(1,45) =11.1, *p* =.002, *F2*(1,184) =12.3, *p* <.001) indicating the increased priming for the +S/M pairs. There was no interaction between Prime and Orthography (*F1*(1,45) =2.4, *p* =.127, *F2*(1,184) =1.3, *p* =.256) nor between Orthography and Semantics (*F1, F2* <1). To establish the source of this interaction, t-tests were performed on individual conditions. There was significant priming in the +S/M, +O condition (*t1*(46) =4.2, *p* <.001, *t2*(47) =5.1, *p* <.001), and the +S/M, -O condition (*t1*(46) =4, *p* <.001, *t2*(47) =4.1, *p* <.001) and these priming effects were not different from each other (*t*1(46) =.-173, *p* =.863, *t2*(47) =.-174, *p* =.864). There was a suggestion of priming in -S, +O condition, though this was marginal by items (*t1*(46) =2.2, *p* =.032, *t2*(47) =1.9, *p* =.062) and no priming in the -S/M, -O condition (*t1*(46) =.179, *p* =.859, *t2*(47) =.023, *p* =.982). There was no difference in the magnitude of priming between these latter two conditions (*t1*(46) =1.5, *p* =.159, *t2*(47) =1.5, *p* =.131) neither between the -S/M, +O condition and the +S/M, +O condition (*t1*(46) =1, *p* =.301, *t2*(47) =1.6, *p* =.117).

Condition	**+S/M, +O (theoria/theoro)**	**-S/M, +O (mania/mana)**
Related primed	571 (0.01)	579 (0.02)
Control primed	592 (0.01)	589 (0.02)
Priming effect	22	10
	+S/M, -O (poto/pino)	**-S/M, -O (tricha/trivo)**
Related primed	568 (0.01)	577 (0.01)
Control primed	588 (0.01)	578 (0.01)
Priming effect	20	1

Table 2. Mean RTs and Error rates (in parentheses) for Experiment 2 (by participants).

Contrary to Experiment 1 delayed priming facilitated responses only in the two conditions that included semantically-related prime-target pairs (+S/M, +/-O). Further, this was the case irrespective of whether the prime was orthographically related to the target (e.g. *theoria/theoro*) or not (*poto/pino*). Although the magnitude of priming was larger in the +S/M, +O conditions than the -S/M, +O condition, there was some suggestion that the semantically unrelated but orthographically related primes (-S/M, +O) facilitated the recognition of their targets (10 ms). This result is consistent with the delayed priming effects reported by Bozic, Marslen-Wilson, Stamatakis, Davis, and Tyler (2007) with English materials, where equivalent priming was observed for pairs like *archer/arch* (semantically and morphologically unrelated) and semantically and morphologically related pairs like *bravely/brave*. Therefore, the weak delayed priming for the *mania/mana* pairs is an intermediate outcome between two outcomes reported in English. An important difference between the present experiment and the delayed priming experiments in English is that the orthographic condition (*mania/mana*) in the present experiment consists of morphologically structured pairs, where both the prime and target can be decomposed into stem and suffix, unlike the orthographic condition in the English studies (e.g. *corner/corn*), where this process can be applied only for prime. Thus, the observation of a weak delayed priming effect for the Greek orthographically related pairs could be based on the common process of morphological decomposition that could be applied equivalently to prime and target. Unfortunately, to our knowledge the previous studies on Greek morphology (e.g. Tsapkini *et al*. 2002) have not included an orthographic condition to allow comparisons with the present results.

4 Experiment 3

Although the ultimate goal of the wealth of behavioral studies on morphological processing has been to provide a plausible account of how words are represented and processed, the brain has been absent for the most part of all these discussions and metaphors concerning the mental lexicon. In addition, most studies have focused on visual words. Only recently, there has been considerable effort to characterize the neural processing stages involved in the recognition of spoken words (e.g. Davis and Johnsrude 2003), as it has already been done for visual words and objects. The number of neuroimaging studies of morphologically complex words, however, comprises mainly studies on inflectional morphology (e.g. Beretta, Campbell, Carr *et al*. 2003) or visually presented words (e.g. Davis, Meunier and Marslen-Wilson 2004). Furthermore, to date, there are no neuroimaging studies of auditory priming between derivationally complex words analogous to the behavioral studies. The current experiment is designed to probe the neural systems that are invoked by derivationally complex words with and without orthographic/phonological changes.

4.1 Method

4.1.1 Participants

18 volunteers took part. All were native speakers of Greek between the ages of 18 and 30 years and right handed. Testing was conducted in Cambridge, UK.

4.1.2 Materials

We used a factorial design involving three prime/target conditions. To allow comparisons with previous fMRI experiments one condition was identity priming (36 words presented twice), which consisted of 18 verbs and 18 derivatives (nouns and adjectives) each of which was presented twice. The remaining two conditions consisted of verb and derivative pairs, either with no orthographic change between them (e.g. θεωρία/θεωρώ*, theoria/theoro*) or with an orthographic change between them (e.g. ποτό/πίνω, *poto/pino*). Three pseudoword conditions were included (36 pairs each, 216 pseudowords). Pseudo-verbs and pseudo-derivatives were constructed in way that mirrored the real word stimuli (i.e. with or without an orthographic change between the prime and the target pseudoword).. A total of 108 word fillers (54 unrelated word/word pairs) and 108 pseudoword fillers (54 unrelated pseudoword/pseudoword pairs) were also included. All the stimuli were recorded by a female native Greek speaker at a sampling rate of 44.1 kHz and edited into separate files for playback using Cool Edit software.

The experimental design included 108 related test word pairs (216 words) and 108 related test pseudoword pairs (216 pseudowords), as well as 54 unrelated filler word pairs (108 filler words) and 54 pseudoword pairs (108 filler pseudowords). This configuration resulted in 432 test trials and 216 filler trials, 648 trials overall. In addition, 172 null-events (instances where no stimulus was presented) were used to provide a resting baseline, resulting in 810 events. Repetitions occurred after approximately 12 intervening items (~30 seconds delay). Priming effects are evaluated within each subject by comparing responses to words that were primed and words that were unprimed. Participants made a lexical decision response to each target.

4.1.3 fMRI scanning technique and data analysis

Imaging was performed on a 3T Bruker scanner using a head coil. Functional images were collected using 21 axial slices angled away from the eyes and covering most of the brain with an echo planar imaging sequence (TR =2.506 ms). To avoid interfering effects of scanner noise, we used bunched image acquisition in which a single volume (TA = 1.1 sec) is acquired, followed by a silent period during which a single stimulus is presented. In each of three experimental sessions (~12 minutes scanning time per session) 285 functional EPI images were acquired. Six images at the start of each run were discarded to allow the EPI signal to reach equilibrium. High-resolution anatomical images (SPGR) and fieldmaps were also acquired for use in preprocessing and normalization. Data were preprocessed and analyzed using Statistical Parametric Mapping software (SPM2, Wellcome Department of Cognitive Neurology, London, UK).

4.2 Neuroimaging results

We were mostly interested in differences in activation between the three priming conditions. A comparison between areas that are activated when the exact same word (Condition1, identical repetitions) is repeated and areas activated when only the stem of the morphological relative is repeated (conditions 2 and 3) would indicate areas involved in representing and accessing the repeated stems. i.e., involved in morphological processing.

First, a 1-way ANOVA was performed contrasting priming for the three conditions only for verb trials but it did not reach a corrected level of significance, both at a whole-brain level and within regions of interest (the areas that show more activation for words than pseudowords). However, the 1-way ANOVA that contrasted priming for the three conditions only for derivative trials revealed a cluster in the left posterior middle temporal gyrus/angular gyrus that showed a trend towards significance at an FDR corrected level (p <.088) and at an FWE level (p <.066) (see Table 3).

Location	Cluster Size	Z	x	y	z
L posterior MTG /Angular gyrus	25	3.55	-52	-56	24

Table 3. The peak voxel that showed a significant difference between the priming conditions for derivatives primed by verbs (words only) within the areas that showed more activation for words than for pseudowords (p(uncorrected) <.001 and FDR p <.088, FWE p <.060).

Based on these results that are indicative at least of a differential pattern of priming in the left middle temporal lobe especially for *theoria/theoro* condition, the priming profile of the left middle anterior temporal lobe cluster (-46, -26, -12) extending into the inferior temporal gyrus that showed more activation for words than for pseudowords was examined in more detail. The parameter estimates for peak voxels of this cluster that showed the lexicality effect were entered into a two-way ANOVA with Condition (3 levels) Lexicality (2 levels, Word/Pseudoword) and Prime (2 levels, primed/unprimed) as within-subjects factors. The results showed a main effect of Condition (F 2,34) =3.402, p <.045) and a Condition by Lexicality interaction ($F(2,34)$ =3.124, p <.057), with more priming for the words (verbs and derivatives collapsed) in the *theoria/theoro* condition.

5 General discussion

5.1 Behavioral data

The experiments in this paper intended to broaden our understanding of the conditions under which semantic and orthographic transparency influence the decomposition of morphologically complex words during recognition and also inform on the neural underpinnings of this process. The results indicate that masked priming is modulated by orthographic opacity but not by semantic opacity: responses were facilitated by orthographically transparent primes but not by orthographically opaque primes. This pattern was not significantly affected by the semantic relationship between prime and target. In Experiment 2, the results indicate that delayed priming is modulated by semantic opacity: responses were facilitated by morphologically and semantically transparent primes but not by semantically unrelated primes that share apparent morphological relationships. This pattern was not affected by the orthographic relationship between prime and target, with equivalent priming for orthographically transparent and opaque pairs.

With regards to the effects of semantic transparency in masked priming, the results from Greek add to the body of evidence from a number of languages for a form of morphological decomposition that is insensitive to semantic characteristics and operates on the basis of apparent morphological complexity. However, in contrast to previous research showing that this form of decomposition is a flexible process that can tolerate regular orthographic alterations (McCormick *et al*. 2008), we found that it is not flexible enough to tolerate more extensive orthographic alterations found in morphologically complex words. Even though the effects of orthographic opacity on masked priming have not been systematically explored, the above observation is corroborated by some previous findings in inflectional morphology. For example, Rueckl, Mikolinski, Miner, Raveh, and Mars (1997) using masked fragment completion found more priming for irregular past tense forms that differed by a single letter from their base form (e.g. *make/made*) than for past tense forms that differed by at least two letters from their base form (e.g. *take/took*) (see also Voga and Grainger 2004 for convergent results in Greek). Similar findings have also been observed in the non-concatenative morphological system of Hebrew (Frost, Deutsch and Forster 2000). However, highly flexible masked priming has been observed in Arabic (Boudelaa and Marslen-Wilson 2005), French (Meunier, Marslen-Wilson and Ford 2000) and Greek (Tsapkini *et al*. 2002) with irregular inflected pairs. Future work will need to specify the exact conditions under which masked priming can appear to be more or less bound to the orthographic appearance of the stimuli (e.g. inflectional vs. derivational morphology). A potentially critical difference between inflectional and derivational morphology is that the latter creates new words, i.e. new lexical entries with new meanings, unlike inflection that does not change the meaning or grammatical category of a word.

With regards to the effects of semantic transparency in delayed priming, the results from the present study are consistent with previous evidence from delayed priming (e.g. Rueckl and Aicher 2008) and other procedures (e.g. cross-modal priming; Gonnerman, Seidenberg and Andersen 2007) for a form of morphological decomposition that is sensitive to the semantic characteristics of the morphologically complex words. The present data also advance our understanding of this form of decomposition in showing unambiguously that it is robust to orthographic opacity. These results extend previous findings of equivalent facilitation in delayed priming for morphological relatives without (*healer/heal*) or with regular orthographic alterations (*health/heal*) (e.g. Fowler, Napps and Feldman 1985).

The divergence of masked and delayed priming in the effects of semantic transparency and to a lesser extent of orthographic opacity provides support for the notion put forward by Rastle and Davis (2008) for two stages in the recognition of morphologically complex words. According to this theory the recognition of morphologically complex words starts with a rapid morphemic segmentation, which decomposes all visual stimuli with an apparent morphological structure, irrespective of their semantic features. This process seems to operate early in visual word recognition, since the priming effects for the semantically unrelated words are usually evident in masked priming but not in other priming paradigms. This rapid morpho-orthographic decomposition can proceed despite orthographic alterations in morphologically complex words but is not flexible enough to survive more extensive orthographic changes. At later points during visual word recognition morpho-orthographic decomposition is replaced by a form of decomposition that is semantically informed (Rastle and Davis 2008). This process is sensitive to the semantic relationship between morphological relatives, operates later in word recognition and is insensitive to orthographic opacity.

A last aspect of the results we wish to consider involves the robustness of delayed priming to orthographic opacity. McCormick *et al.* (2008) explained the robustness of masked priming to regular orthographic changes (e.g. missing 'e') in terms of the underspecification of stems that undergo regular orthographic changes. The authors argued that such stems may be represented orthographically such that surface variations can be tolerated once a suffix is segmented (e.g. by marking a final "e" as optional). Thus, the orthographic representation of a stem like *adore* may include an underspecified final 'e', which would allow the activation of the stem for derived words like adorable where the final 'e' is missing. However, it is difficult to envisage how this would be possible for the extensive and unpredictable changes to the stem in the case of the orthographic opacity. One possible mechanism discussed by Marslen-Wilson and Tyler (1998) for the recognition of auditory irregular inflected words in English is that both phonological alternants of irregular verbs are listed, but they share semantic and syntactic features. By analogy to visual word recognition then, we could argue that for words that undergo extensive orthographic changes to their stems, there are separate orthographic representations of the two stems but their semantic and syntactic features are common (see also Tsapkini *et al.* 2002). This would explain why priming is not observed for this kind of words in masked priming but they do emerge in delayed priming.

To conclude, the experiments reported here provided definitive evidence that semantically transparent primes produced more facilitation in delayed priming than semantically opaque primes, while orthographically transparent primes produced more facilitation in masked priming than orthographically opaque primes. However, there was some suggestion that semantically opaque primes facilitated recognition of their targets in delayed priming, and similarly for orthographically opaque primes in masked priming. A complete theory of the nature of the representations used in skilled reading will have to determine precisely the weight of the different kinds of information (orthographic, semantic) during visual recognition of the various types of words encountered by readers of different languages (e.g. irregularly inflected words, semantically opaque words) and how these characteristics are reflected in different behavioural indices.

5.2 Neuroimaging data

The fMRI study presented in this chapter was an attempt to find evidence of morphological structure at a neural systems level. Despite the enormous interest in establishing morphology as a distinct linguistic entity, research looking at effects of morphology at the neural level is almost in its infancy compared to the abundance of behavioural studies on morphological processing. Evidence for an effect of morphological structure was seen in the left middle temporal gyrus (anterior and posterior, bordering angular gyrus). In particular, two clusters in this area (-46, -26, -12 and -52, -56, 24) showed more priming for pairs like *theoria/theoro* than in any other condition. The comparison of identity priming with morphological priming, both with a stem change and without, did not reach significance in any other cluster.

It has been suggested that the left middle temporal gyrus is crucial for the activation of phonological word forms (Price, Wise, Patterson, Howard and Frackowiak 1994). Several studies have shown the engagement of this area during semantic and phonological tasks, but the activation has been consistently stronger during the semantic tasks (e.g. Demonet, Chollet, Ramsay *et al.* 1992). This is consistent with the claim that the middle temporal gyri also play a role in the processing of the word meanings associated with the activated word form (Pugh *et al.* 1996). Elevated activation in an area (-50, -48, -10) adjacent to middle temporal cluster that showed the increased priming for the morphologically complex words in the no stem change condition has been reported for sentences containing ambiguous words compared to sentences that did not contain ambiguity (Rodd, Davis and Johnsrude 2005).

Thus, the present results suggest an important role for the middle/posterior temporal areas in accessing an abstract representation of the form and meaning of morphologically derived words, consistent with the claims made by Hickock and Poeppel (2000). Furthermore, it is conceivable that this abstract representation corresponds to the shared stem morpheme between the two words. This conclusion is reinforced by the lack of priming in this area for pairs like *poto/pino*, which are possibly treated as two different lexical items with two distinct stems. Admittedly, the present study, apart from the two clusters in the middle temporal lobe, did not show strong effects of neural priming between morphologically related words. Other studies that have looked at neural responses when subjects had to perform some kind of task involving inflectional and derivational processes (Beretta, Campbell, Carr, Huang *et al.* 2003; Marangolo, Incoccia, Pizzamiglio, Sabatini, Castriota-Scandenberg and Burani 2003) observed more widespread increased activation associated with morphological processes. Tyler, Marslen-Wilson, and Stamatakis (2005) reported activations specific to inflected items in frontal and temporal lobe areas in a study where participants had to perform semantic judgements on regular-, irregular and pseudo-inflected verbs and nouns. However, using a synonym-monitoring task, Davis *et al.* (2004) did not observe any differences between the processing of morphologically simple and morphologically complex words (inflected or derived). It should be noted though that the extent to which the brain regions activated for these tasks reflect processes that take place during natural language use has been called into question (Davis and Johnsrude 2003). In the lexical decision task used here, and in most behavioural studies that have obtained morphological priming, overt processes of decomposition are not explicitly demanded for adequate task performance.

The pattern of results is too inconsistent to justify strong claims about the presence of specific neural systems that handle morphological complexity or the absence of specific neural mechanisms devoted to morphological processing (e.g. Plaut and Gonnerman 2000). More neuroimaging studies using the methodology of the behavioural studies are needed to explore, whether the robust morphological priming effects, that are obtained behaviourally irrespective of task and mode of presentation, can be obtained at the neural level. Until then, the current neuroimaging data should be treated only as indicative of a model of lexical processing where abstract phonological representations are computed in the superior temporal lobes while lexical/semantic representations, possibly coding for morphological structure, are accessed in left middle/posterior temporal areas.

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