Morphological processing in adults and children during visual word recognition

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Contents

Declaration

The research presented in this thesis is my original work and it has not been submitted for a higher degree in any other institution. In addition, I certify that all information sources and literature used are indicated in the thesis.

I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged. The research presented in this thesis was approved by Macquarie University Ethics Review Committee (HE24NOV2006-R04946C and HE24AUG2008-RO5406).

The following chapters from this thesis have been accepted for publication.

Beyersmann, E., Castles, A., & Coltheart, M. (in press). Early morphological decomposition during visual word recognition: Evidence from masked transposed-letter priming. *Psychonomic Bulletin & Review.*

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It should be noted that these articles have been included in this thesis in an unchanged format and as such there is a degree of repetition across the Introduction and Method sections of these chapters.

Signed:

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Thesis summary

The research presented in this thesis examines cognitive processes involved in the recognition of written morphologically complex words in skilled readers and the acquisition of these mechanisms in developing readers. All experiments focus on non-strategic aspects of rapid morphological segmentation, exploring the nature of underlying lower-level orthographic processing constraints in morphological decomposition. The influences of orthographic processing constraints upon morphological processing are explored by distinguishing between lower-level *morpho-orthographic* and higher-lever *morpho-semantic* processing mechanisms. The introductory thesis chapter reviews evidence of different forms of purely structural non-semantic morphological processes and discusses the implication for morphological processing theories as well as orthographic processing theories. The role of morphological decomposition in visual word recognition is then examined across four different chapters (testing 446 adult participants and 72 children), in both English and Spanish native speakers. To explore non-conscious stages of cognitive processing, the present research draws upon the *masked priming paradigm*, providing a window into early, automatic processes in visual word recognition. In Chapters 2, 3, and 4, a novel approach is used combining the masked priming paradigm with the *transposed-letter priming paradigm* to examine if and how the encoding of morphological information is modulated by lower-level letter position processing mechanisms, in skilled readers. The final chapter provides a summary of the presented findings across all chapters and gives an outlook on future research prospects. We conclude that morphological processing in both skilled and developing readers is based on both morpho-orthographic and morpho-semantic processing mechanism, which we discuss in the context of current morphological processing theories.

Introduction

Introduction

Written language is one of our main means of communicating with other people. It allows us to communicate our thoughts, ideas and needs to other people and is essential for normal social interactions. The ability to read is one of the most valuable human skills. Understanding the mechanisms involved in reading words are therefore of great practical relevance as well as theoretical interest. Particularly, insights from cognitive science provide an important window to the structure and processing mechanisms of the human reading system. However, current models of visual word recognition are still underspecified.

One of the most significant challenges in research on reading, has been the processing of morphologically complex words (e.g. *reader*, *reading*, *reread*, etc). Morphological knowledge is an important basis for language processing, as it requires the mastery of critical linguistic concepts (e.g. plural formations, grammatical person information, past tense formations, etc.). It is therefore important to assess the cognitive architecture of the morphological parsing system to specify theories of written language. Yet many puzzles still remain as to the cognitive processes involved in the visual mapping of words onto abstract representations in the brain. The reconciliation of different morphological processing hypotheses is therefore a central aim of this thesis. Current evidence for the visual processing of morphologically complex words primarily stems from research on adults. The present introductory chapter examines these data in the context of existing morphological processing accounts and provides an outlook on possible directions for future research. Chapters 2-4 report on experiments designed to explore the nature of the morphological parsing system in adults, with particular emphasis on very early subconscious stages of reading. Chapter 5 presents an initial study exploring the development of the morphological parsing system in children. The final chapter then reviews the proposed links between morphological and lower-level orthographic processes as well as higher-level semantic processes during reading. This chapter particularly focuses on the evidence reported in Chapters 2-6 which is discussed in the context of different morphological processing and morphological acquisition accounts, and examines directions for future research.

Recent trends in morphological processing

Many decades of research have been directed towards understanding how and when readers gain access to morphological information in visual word recognition (Aronoff, 1994; Baayen, Burani, & Schreuder, 1997; Bybee, 1995; Colé, Beauvillain, & Segui, 1989). It has been proposed in some instances that morphologically complex words are fully listed in the orthographic lexicon, therefore no morphological decomposition is needed (e.g. Burani & Caramazza, 1987; Burani & Laudanna, 1992; Caramazza, Laudanna, & Romani, 1988). In recent years however, more and more research has supported the idea that morphologically structured words are decomposed into their morphemic subunits during visual word recognition, which is by now a widely accepted view. However, there is still uncertainty as to what mechanisms are used to process morphologically complex words during reading.

Support for the theory of morphological decomposition has come from a range of sources. For instance, frequency measures have been used to investigate the role of stem morphemes (e.g. *read*, as in *reading*) in complex word processing showing that the stem frequency influences the time it takes to recognise the word (e.g. Bertram, Schreuder, & Baayen, 2000; Niswander, Pollatsek, & Rayner, 2000; Taft, 1979). Masked priming has also been a popular method to explore complex word recognition showing that the recognition of a stem target (*corn*) is facilitated by the prior presentation of a morpho-orthographically related (*corner*) prime (Forster & Davis, 1984; Rastle, Davis, Marslen-Wilson, & Tyler, 2000). Moreover, electrophysiological measures (e.g. Dominguez, de Vega, & Barber, 2004; Lavric, Clapp, & Rastle, 2007; Morris, Frank, Grainger, & Holcomb, 2007; Morris, Holcomb, & Grainger, 2008), functional magnetic resonance imaging (Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Devlin, Jamison, Matthews, & Gonnerman, 2004; Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005), and eye-tracking (e.g. Juhasz, 2008; Kuperman, Bertram, & Baayen, 2008; Pollatsek, Slattery, & Juhasz, 2008) have been used to investigate the nature of morphological decomposition. Neural sensitivity to morphology has also been reported in patients with acquired dyslexia (Hamilton & Coslett, 2008) and patients with damage in the left inferior frontal gyrus (Tyler, Marslen-Wilson, & Stamatakis, 2005). Moreover, empirical evidence favouring the decomposition of polymorphemic derived words has been obtained in several languages such as Hebrew (Bentin & Feldman, 1990; Deutsch, Frost, & Forster, 1998; Frost, Forster, & Deutsch, 1997), German and Dutch (Diependaele, Sandra, & Grainger, 2005; Drews & Zwitserlood, 1995), Spanish (Badecker & Allen, 2002; Duñabeitia, Perea, & Carreiras, 2007; Duñabeitia, Perea, & Carreiras, 2008), French (Grainger, Colé, & Segui, 1991; Longtin & Meunier, 2005; Longtin, Segui, & Hallé, 2003a) and English (Feldman, 2000; Rastle et al., 2000; Rastle, Davis, & New, 2004).

While the variety of evidence demonstrates that morphological decomposition has been extensively explored, the past decades of research have also yielded a number of disagreements regarding the type of information readers use to process the internal structure of morphologically complex words. Two key mechanisms have been proposed to underlie the morphological parsing of written words. The first mechanism, as evidenced by a large variety of experimental data, decomposes any morphologically complex letter strings into orthographically defined morphemic units (*morpho-orthographic* units), based on the mere appearance of morphological complexity. The second mechanism decomposes morphologically complex words into semantically defined morphemic units (*morpho-semantic* units), and this occurs for semantically transparent words only. This debate also raises the question whether the recognition of morphologically complex words is uniquely based on morphemic decomposition, or if whole-word recognition of morphologically complex words is also possible, or both. This question becomes particularly relevant in the context of different proposed morphological processing theories, which we discuss in more detail below. At present, there is still no common understanding of *how* and *when* exactly in the reading system morphologically complex words are decomposed.

In this introductory review chapter, we first discuss diverging results of previous research, specifically in relation to the broad range of evidence in support of morpho-orthographic processing. Then we briefly consider the role of morpho-semantic processing in visual word recognition. Finally, we consider this evidence in the context of both morphological and orthographic processing theories, and discuss critical theoretical implications and directions for research.

Morpho-orthographic processing

Morpho-orthographic processing of suffixed words. Rastle et al. (2004) were the first to report evidence for non-strategic morpho-orthographic processing of written words in English (see Longtin et al., 2003a, for related evidence in French). Rastle and colleagues carried out a masked priming lexical decision experiment using three different types of prime. In the first condition, stem targets were preceded by *truly suffixed* primes, comprising a semantically transparent prime-target relationship (*darker-DARK*). In the second condition, targets were preceded by *pseudo-suffixed* primes, in which the meaning of the whole-word could not be derived from the meaning of its morphemic subunits (*corner-CORN*). In addition to the two morphological conditions, they introduced a third *non-suffixed* control condition. The orthographic control items were chosen such that there was an orthographic, but no morphological or semantic overlap between prime and target (*brothel-BROTH*). Most importantly however, the orthographic control primes were all monomorphemic, comprising non-morphemic endings (*el*). Primes were presented in lowercase for 42 ms preceded by a 500 ms forward mask and followed by the targets presented in uppercase (*darker-DARK*, *corner-CORN*, *brothel-BROTH*, etc.).

The results showed priming in the truly suffixed (*darker-DARK*) and in the pseudo-suffixed condition (*corner-CORN*), but not in the orthographic control condition (*brothel-BROTH*), providing evidence relevant to three important questions. Firstly, morphological priming was found with only 42ms of presentation duration, suggesting that morphological information is accessed at early subconscious stages in visual word recognition. Secondly, the findings showed that the priming effects found were not simply due to orthographic overlap. Thirdly, and most importantly, the data indicated that morphological decomposition occurs independently of whether complex words bear a true morphological structure (*darker*) or just a morphological pseudo-structure (*corner*) suggesting that morphological decomposition is not controlled by the semantic or syntactic relationship between the lexical representations of prime and target.

Rastle et al.'s (2004) findings have been replicated across different Indo-European languages (for a review, see Rastle & Davis, 2008), as standardly evidenced by significant magnitudes of priming obtained for both truly suffixed (*darker-DARK*) and pseudo-suffixed prime-target pairs (*corner-CORN*).

Morpho-orthographic processing of prefixed words. Support for the theory of pre-lexical morphological decomposition also comes from the study of prefixed primes. For instance, Smolka, Komlósi and Rösler (2009) used unmasked priming to compare lexical decision responses to truly prefixed (*mitkommen-kommen* [*come along-come*]) and pseudo-prefixed primes (*umkommen-kommen* [*perish-come*]), relative to a semantic (*nahen-kommen* [*approach-come*]), an orthographic (*kämmen-kommen* [*comb-come*]), and an unrelated control condition (*schaden-kommen* [*harm-come*]), in German. Morphological priming was equally obtained for both truly and pseudo-prefixed words, and was significantly stronger than in the semantic and unrelated control conditions. Moreover, there was a significant inhibition effect in the orthographic control condition, suggesting that the obtained effects were not due to the orthographic relatedness between prime and target. Consistent with the evidence reported for suffixed words, these findings provide evidence in support of a morpho-orthographic decomposition hypothesis, suggesting that prefixed words are decomposed independently of semantic relatedness.

In a related study in English, Diependaele, Sandra & Grainger (2009, Experiment 1) compared three different types of English prefixed 40 ms primes in a masked primed lexical decision task. A truly prefixed (*rename-NAME*) and a pseudo-prefixed condition (*relate-LATE*) were compared to a non-suffixed control condition (*entail-TAIL*). In line with Smolka et al. (2009), these results revealed equal magnitudes of priming in the truly prefixed and pseudo-prefixed condition, but no priming was obtained in the orthographic condition suggesting that prefix-stripping is semantically blind (for related evidence on prefixed bound-morphemes, see M. Taft & K.I. Forster, 1975; Taft, Hambly, & Kinoshita, 1986).

Morpho-orthographic processing of nonwords. More recently, Longtin & Meunier (2005) were the first to extend these findings to a situation where the prime is not a word (see also Pollatsek et al., 2008, for related evidence in English). Their experiments were conducted in French and compared priming effects on stems of both semantically interpretable nonword primes (*rapidifier-*

RAPIDE [*quickify-QUICK*]) and semantically non-interpretable nonword primes (*sportation-SPORT* [*sportation-SPORT*]) and found similar-sized effects[1]. Priming occurred for semantically interpretable and semantically non-interpretable nonword primes, but not when the presented primes were non-morphological nonwords (*rapiduit-RAPIDE* where *uit* is not a suffix), showing that the priming in the morphological conditions was not due to a simple orthographic overlap. Their results suggest that morphological decomposition applies to all morphologically structured items, even if they are not words. These findings take the evidence for pre-lexical affix-stripping one step further: the stem priming obtained of morphologically structured nonword primes even more clearly point towards a segmentation mechanism which purely operates on the analysis of orthography. Given that the materials tested by Longtin and Meunier (2005) are not represented as lexical units in the visual word recognition system, makes it difficult to attribute the obtained priming effects to a higher-level mechanism of morphological decomposition.

Morpho-orthographic processing of words and nonwords with orthographic alterations. A question that arises is whether the morpho-orthographic parsing system only operates under the premise that a given morphological input stimulus is perfectly segmentable into its morphemic subunits (*corn+er*, *sport+ation*, etc.), or if morphological analysis is also successful in words with orthographic alterations (*ador(e)+able*, *drop(p)+er*, etc.). To address this question, McCormick, Rastle, & Davis (2008) conducted a set of masked primed lexical decision experiments to examine three different types of morphological alterations: missing 'e' (*adorable-ADORE*), shared 'e' (*lover-LOVE*), and duplicated consonant (*dropper-DROP*), which all three revealed significant priming. These examinations were then extended to the context of orthographically altered pseudo-affixed word primes (*committee-COMMIT*, *badger-BADGE*, and *fetish-FETE*; McCormick et al. 2008), and orthographically altered affixed nonword primes (*adorage-ADORE*; McCormick, Rastle, & Davis, 2009). Significant priming was found in each condition. McCormick et al.'s findings thus indicate that morpho-orthographic decomposition is robust to regular orthographic alterations found in (i) truly affixed words (for related evidence in German, see also Clahsen, Eisenbeiss, Hadler, & Sonnenstuhl, 2001; and see also Gaskell, Hare, & Marslen-Wilson, 1995; Gaskell & Marslen-Wilson, 1998, for evidence from auditory word recognition) and that such parsing mechanism even appears to tolerate orthographic alterations in a (ii) pseudo-morphological and (iii) morphologically complex nonword context.

[1] Semantically interpretable nonwords (*rapidifier*) comprised syntactically legal combinations of suffix and stem (*fier* combines with adjectives, *rapid* is an adjective), whereas semantically non-interpretable nonwords (*sportation*) consisted of syntactically illegal combinations of a suffix and a stem (*ation* combines with verbs, but *sport* is a noun).

Based on an account firstly proposed by Taft (1979), McCormick and colleagues hypothesized that robustness of the morpho-orthographic segmentation system is achieved through the orthographic underspecification of the morphemic stem. For instance, the orthographically altered input stimulus *adorable* would be decomposed into orthographically underspecified stem *ador* and suffix *able.* Due to the regularity of the alternating pattern (e.g. missing 'e'), the recognition system memorizes the alternated representation *ador* as an optional marker for *adore* in the orthographic lexicon. The linkage between the orthographically underspecified representation of the stem (*ador*) and the representation of its corresponding real stem (*adore*), is what thus produces the observed effects of priming (e.g. *adorable-ADORE, adorage-ADORE*, etc.).

Position-specific morpho-orthographic processing. In recent years, *transposed-letter similarity effects* have allowed researchers to shed new light onto the nature of morpho-orthographic processing. Previously, transposed-letter (TL) priming effects have primarily been explored in the context of monomorphemic word processing. For instance, Perea and Lupker (2003) showed that, while the recognition of a target word is facilitated by the prior presentation of a prime that differs from the target with respect to the transposition of two letters (*d**ra**k-DARK*), such facilitatory priming effects are not obtained of substituted-letter primes (*d**ce**k-DARK*). Such evidence suggests that early stages of orthographic analysis operate with high positional uncertainty, therefore orthographic representations of monomorphemic words are robust to orthographic alterations such as letter transpositions. Only recently, have transposed-letter priming effects begun to be applied to the study of morphologically complex words, to test if the morpho-orthographic parsing system tolerates transposed-letter alterations. If morphological processes coincide with lower-level letter position encoding stages, this would strongly suggest a very early orthographic locus of morphological segmentation during reading.

Christianson, Johnson, & Rayner (2005) found evidence for the disappearance of transposed-letter priming across morphemes in both derivationally suffixed words (*boas**et**r-BOASTER*) and compounds (*sil**wk**orm-silkworm*), using a masked primed naming task in English. Similarly, a related masked primed lexical decision study in Spanish and Basque by Duñabeitia et al. (2007) revealed that prefixed and suffixed words with within-morpheme boundary transpositions (*meosnero-MESONERO* [*brakeeper-BARKEEPER*]) produced significant TL-priming, whereas no priming was obtained when letters were transposed across the morpheme boundary (*mesoenro-MESONERO* [*bakreeper-BARKEEPER*]). These findings indicate that letter manipulations at the morphemic boundary between stem and suffix disrupt the segmentation into morphemes. The orthographic specification of morpheme-boundary representations thus seems to play a particularly important role in the reading system.

One explanation for the reduced magnitudes of across-boundary priming reported by Christianson et al. and Duñabeitia et al. may be that morpheme-external letters (i.e. the last letter of the stem and the first letter of the suffix) are encoded with higher positional certainty than morpheme-internal letter positions. In the context of monomorphemic words, it has, for example, been shown that TL-nonwords with transpositions at external positions resemble their corresponding real word to a lesser degree than TL-nonwords with transpositions at internal positions (Johnson, Perea, & Rayner, 2007; Perea & Lupker, 2007; Rayner, White, Johnson, & Liversedge, 2006), suggesting that the orthographic boundaries of monomorphemic words are coded with higher positional certainty than the word-internal letter positions. Alternatively, it is also possible that the orthographic encoding of affixal units generally requires greater positional specificity than the orthographic encoding of stems, and is therefore less robust to orthographic alterations. Further research is needed to clarify this question.

Challenging for the accounts above has been some other evidence demonstrating that across morpheme-boundary transpositions do not always disrupt priming (Perea & Carreiras, 2006; Rueckl & Rimzhim, 2010). For instance, Rueckl and Rimzhim (2010; for converging evidence, see also Perea & Carreiras, 2006) reported significant masked TL-priming for both within-boundary and across-boundary transpositions, independently of whether the presented targets were stems (*tea**hc**er-TEACH*) or whole-words (*tea**hc**er-TEACHER*). These findings suggest that there is a mechanism that allows the word recognition system to overcome a break-down of the morphological decomposition route through across-morpheme boundary transpositions. One possibility is that the reading system switches to processing the input string based on its whole-word representation (Perea & Carreirras, 2006), permitting word recognition regardless of across-boundary transpositions. However, further systematic investigations of morpheme-boundary transpositions are needed to precisely understand the nature of orthographic representations in reading complex words and the factors that influence position-specificity in morphological parsing (see also Chapters 2-4).

A related issue also deserving attention is whether the morpho-orthographic parsing system tolerates transpositions of not just single letters, but also of letter sequences of two letters or more. Crepaldi, Rastle & Davis (2010b) investigated morphological decomposition by moving suffixes into word-initial position. Crepaldi et al. carried out an unprimed lexical decision task showing that suffixed nonwords (*gasful*) were classified more slowly than their orthographic controls (*gasfil*). However, there was no such difference neither when stem and suffix of suffixed nonwords were reversed (*fulgas* vs. *filgas*) nor when stem and suffix of suffixed real words were reversed (*nesskind* vs. *nusskind*). Hence, these results strongly support the hypothesis that suffix identification is position specific. Such position-specific constraints may well play a useful role in the morphological parsing system, as they would prevent the inappropriate over-generation of morphemic units (e.g.

strip *er* of *error*) and thus "enable a putative affix-stripping mechanism to operate more efficiently without unduly increasing its complexity or capacity for rapid automatic decomposition of morphologically complex words" (Crepaldi et al., 2010; pp. 319).

Position-independent morpho-orthographic processing. In contrast to the evidence presented above suggesting that the encoding of affixes requires at least some degrees of position-specificity, studies examining letter and morpheme transpositions have revealed that the morphological parsing system indeed tolerates certain types of positional alterations. It has, for example, been found that, if letters are transposed within truly affixed words without disrupting the morphemic boundary (*wlaker-WALK*; e.g. Duñabeitia et al. 2007; Rueckl & Rimzhim, 2010), significant stem-target priming can be obtained. These findings suggest that morphological decomposition of truly affixed words is robust to stem-internal transpositions.

Further evidence in support positional-independence in morphological processing, comes from Crepaldi, Rastle, & Davis (2010a) who reported that in the context of a lexical decision task, in English, reversed compounds (*moonhoney*) take longer to reject than matched control nonwords (*moonbasin*), which seems to indicate that the identification of stem morphemes is position-independent (see also Duñabeitia, Laka, Perea, & Carreiras, 2009, for related evidence from Basque). Similarly, evidence for position-independent morphological decompositions also comes from the study of prefixed words. Previous research reveals that significant priming is obtained from (i) prefixed primes to stem targets (e.g. *rename-NAME*; Diependaele et al., 2009), and (ii) from prefixed prime to suffix target (e.g. *distrust-TRUSTFUL*; Marslen-Wilson et al., 1994), indicating that priming occurs despite the deviating position of the stem morpheme (word-final position in the prime, and word-initial position in the target).

Morpho-semantic processing

Morpho-semantic processing of suffixed words. Evidence for morpho-semantic processing has been found using the unmasked cross-modal priming paradigm. For instance, Marslen-Wilson, Tyler, Waksler, & Older (Marslen-Wilson, Tyler, Waksler, & Older, 1994) investigated the role of morphological derivations in lexical access using an unmasked cross-modal priming task, with auditorily presented primes and visually presented targets. Priming effects were obtained of true morphological structures (*friendly-FRIEND, insincere-SINCERE* [derived-stem]*, confession-CONFESSOR, unfasten-REFASTEN, distrust-TRUSTFUL, judgement-MISJUDGE* [derived-derived], *friend-FRIENDLY* [stem-derived]), but not for morphological pseudo structures (*authority-AUTHOR, restrain-STRAIN* [derived-stem]*, successful-SUCCESSOR, depress-EXPRESS* [derived-derived], *apart-*

APARTMENT [stem-derived]) or non-morphological structures (*bulletin-BULLET*). These findings suggest that the morpho-orthographic relationship between prime and target is not sufficient to produce unmasked cross-modal priming (see also Longtin et al., 2003a). These data provide clear evidence for a morphological segmentation mechanism which operates only in the presence of a morpho-semantic prime-target relationship.

In a related study in French, Meunier & Longtin (2007) carried out three lexical decision experiments using an unmasked cross-modal design with auditory primes and visual targets. Stem and suffixes were combined in different ways such that they either formed an existing derived word form (*garagiste-GARAGE* [*mechanic-GARAGE*]), an semantically non-interpretable stem-suffix combination (*garagité-GARAGE* [*garagement-GARAGE*]), or a semantically interpretable stem-suffix combination (*rapidifier-RAPIDE* [*quickify-QUICK*]). The morphological conditions were compared to an unrelated (*diversion-GARAGE* [*diversion-GARAGE*]) and orthographic control condition (*rapiduit-RAPIDE* [*quickel-QUICK*]). The findings revealed priming in the derived word form condition and in the semantically interpretable condition, but not in any of the other conditions. In line with Marslen-Wilson et al., Meunier & Longtin's (2007) data thus indicate that overtly presented nonword primes facilitate the recognition of their stem targets, but only in the presence of a semantically interpretable relationship.

Semantic effects on morphological processing have also been evidenced by masked primed lexical decision studies using prime durations of 50+ ms. For instance, Rastle et al. (2000) compared masked priming effects obtained of truly suffixed (*departure-DEPART*) and pseudo-suffixed primes (*apartment-APART*) to the stem target using three different prime durations (43 ms, 72 ms, and 230 ms). While the truly suffixed condition revealed significant priming at all three prime durations, pseudo-suffixed priming only emerged at the shortest prime duration, and decreased as prime duration increased. These findings indicate that effects of semantics onto morphological processing become increasingly more notable when participants are given more time to process the prime (see also Giraudo & Grainger, 2001; H. Giraudo & J. Grainger, 2003b).

Morpho-semantic processing of prefixed words. In the context of a unmasked cross-modal priming task (with auditorily presented primes and visually presented targets), Marslen-Wilson et al. (1994) compared truly prefixed prime-target pairs (*insincere-SINCERE* [derived-stem], *unfasten-REFASTEN* [derived-derived]) to pseudo-prefixed prime-target pairs (*restrain-STRAIN* [derived-stem], *depress-EXPRESS* [derived-derived]), revealing priming for truly prefixed, but not for pseudo-prefixed primes. This effect of semantic transparency thus confirms the idea that there is a morphological segmentation mechanism which operates over morpho-semantic structures only (for converging evidence, see also Diependaele et al., 2009).

Implications for morphological processing theories

The review of the literature shows that, while the visual masked priming procedure appears to be particularly sensitive to the lower-level morpho-orthographic form features of a letter string (Gold & Rastle, 2007; Kazanina, Dukova-Zheleva, Geber, Kharlamov, & Tonciulescu, 2008; Lavric et al., 2007; Marslen-Wilson, Bozic, & Randall, 2008; Morris et al., 2007; Rastle & Davis, 2008; Rastle et al., 2004), evidence for higher-level morpho-semantic processing has been primarily obtained from studies using partially or fully overtly presented primes (Bozic et al., 2007; Drews & Zwitserlood, 1995; Gonnerman, Seidenberg, & Andersen, 2007; Longtin et al., 2003a; Marslen-Wilson et al., 1994; Meunier & Longtin, 2007; Rastle et al., 2000; Rueckl & Aicher, 2008), suggesting that the degree of visibility of the prime affects the depth of stimulus processing. These empirical data have critical theoretical implications for current models of morphological processing, which we consider below.

Current theories of morphological processing can be summarized in four main classes: *obligatory decomposition theories*, *supra-lexical decomposition theories*, *form-then-meaning theories* and *parallel dual-route theories*. Obligatory decomposition theories consider that morphologically complex words are exclusively decomposed on basis of morpho-orthographic structure analysis (Taft, 1994, 2003), and thus fail to account for morpho-semantic priming effects. Supra-lexical decomposition theories suggest that morphologically complex words are exclusively decomposed on basis of morpho-semantic structure analysis (e.g. Giraudo & Grainger, 2001; H. Giraudo & J. Grainger, 2003b), and thus fail to account for morpho-orthographic priming effects. Form-then-meaning theories and the parallel dual-route theories however, can account for both morpho-orthographic and morpho-semantic processing.

Form-then-meaning theories postulate that there is an initial obligatory morpho-orthographic processing stage which is followed by a later morpho-semantic processing stage (Crepaldi, Rastle, Coltheart, & Nickels, 2010; Rastle & Davis, 2008). While morpho-orthographic processing applies to any letter string with the mere appearance of morphological complexity (e.g. *darker* [truly suffixed], *corner* [pseudo-suffixed], *quickify* [semantically interpretable nonwords], and *sportation* [semantically non-interpretable nonwords]), morpho-semantic processing affects true morphological structures only (e.g. *darker*; see Figure 1).

Parallel dual-route theories propose that morphologically complex words are simultaneously processed via a morpho-orthographic segmentation route, which decomposes any stimulus pre-lexically into its morphemic subunits, and a morpho-semantic segmentation route, which carries out a post-lexical search for shared representations at the morpho-semantic level and decomposes any word bearing a true morphological structure (e.g. Baayen, Dijkstra, & Schreuder, 1997; Diependaele et al., 2009; see Figure 2).

Both form-then-meaning theories and parallel dual-route theories yield two critical predictions that are examined in this thesis. First, one of the most fundamental questions of morphologically processing that remains to be addressed is whether morphologically complex words are always recognised on basis of their stem morphemes or if direct access to the representation of the whole-word is also possible. Second, our research aims to systematically explore the interplay of morpho-orthographic and morpho-semantic processing mechanisms, to examine whether initial stages of morphological decomposition are uniquely based on an orthographic type of analysis which is then followed by a semantic type of analysis, or if it is due to a combination of morpho-orthographically and morpho-semantically guided parsing into morphemes.

Answers to these questions are critical to distinguish between form-then-meaning and parallel dual-route theories. Insights gained from such research will further the understanding of how morphologically complex words are processed, and thus provide an essential specification of the human reading system.

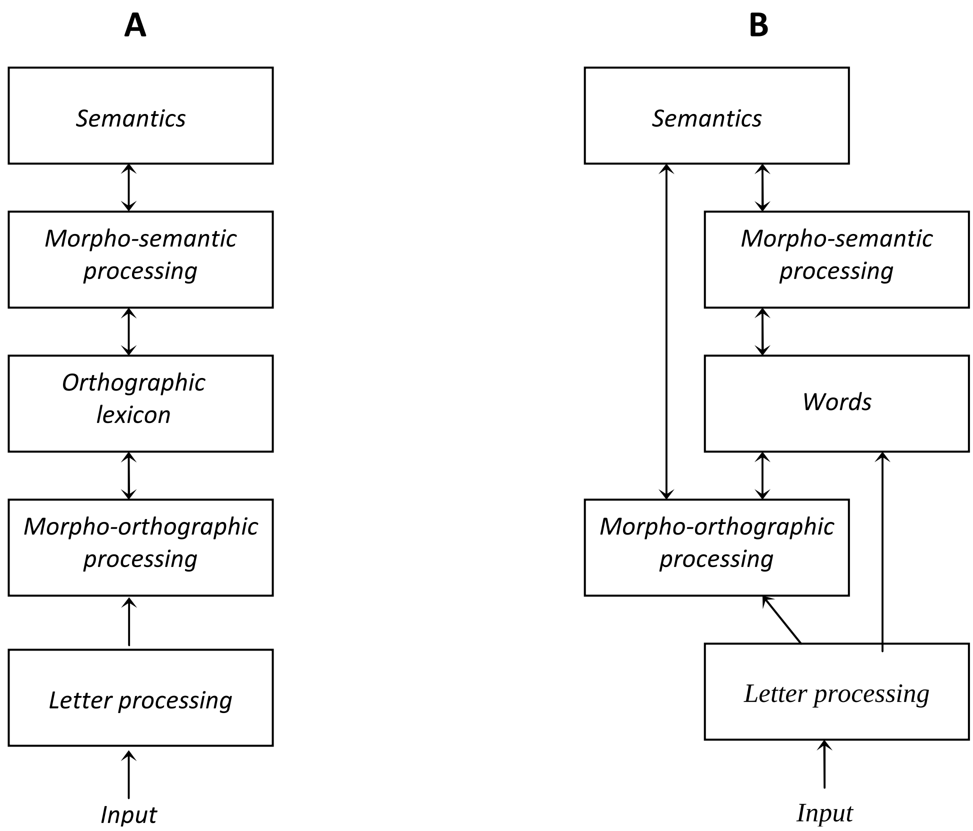

Figure 1: A: Graphic representations of form-then-meaning accounts (Crepaldi, Rastle, Coltheart et al., 2010; Rastle & Davis, 2008). B: The presented model is based on parallel dual-route accounts (Baayen, Dijkstra et al., 1997; Diependaele et al., 2009; Feldman, O'Connor, & Moscoso del Prado Martin, 2009).

Implications for letter-position coding theories

Previous work has revealed controversial results regarding the role of letter position decoding in morphological processing. As discussed, while one body of evidence proposes that morphological processing is based on precise letter position information (Christianson et al., 2005; Crepaldi, Rastle et al., 2010b; Duñabeitia et al., 2007), it has also been demonstrated that morphological parsing operates over very early orthographic processing stages with high positional uncertainty (Crepaldi, Rastle et al., 2010a; Duñabeitia et al., 2007; Rueckl & Rimzhim, 2010). Taken together, these findings seem to suggest that the degree of letter position specificity may vary at different positions in the letter string, which has critical implications for current theories of orthographic processing.

Current letter position coding theories can be summarized in four main classes: *Slot-coding theories, Wickelcoding theories, Open-bigram Coding theories* and *Spatial Coding theories* (for a review, see C. J. Davis & Bowers, 2006). First, Slot-Coding theories postulate that every letter position is coded by activating a separate slot for each letter (e.g. 'cat' activates the three letter codes C1, A2, and T3; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 1999; Hinton & Shallice, 1991; McClelland & Rumelhart, 1981; Paap, Johansen, Chun, & Vonnahme, 2000; Paap, Newsome, McDonald, & Schvaneveldt, 1982). Second, Wickelcoding theories assume that letter position is coded in relation to its surrounding letters (e.g. 'cat' is coded as a set of 'Wickelfeatures': _ca, cat, at_; Rumelhart & McClelland, 1986; Seidenberg & McClelland, 1989; Wickelgren, 1969). Third, Open-Bigram theories consider that letter position information is based on the encoding of ordered bigrams (e.g. 'cat' is coded as a set of open-bigrams 'ca', 'ct', 'at'; Grainger & van Heuven, 2003; Grainger & Whitney, 2004; Schoonbaert & Grainger, 2004; Whitney, 2001; Whitney & Berndt, 1999). Fourth, Spatial Coding theories assume that all letter units are independent of position context, coded from left to right, such that different letter orders result in different spatial patterns of activity (C. J. Davis, 1999, 2010). According to this theory, all of the letters in a word are coded with equivalent signal strengths and each letter position contributes equally to the computation of similarity between the input letter string and an existing lexical entry.

Over the last decades, letter position coding theories have been challenged by the increasing number of studies reporting transposed-letter priming effects. Particularly, Slot-coding and Wickelcoding theories have difficulty accounting for the greater magnitude of transposed-letter priming relative to the magnitude of substituted-letter priming. Slot-coding theories postulate that transposed-letter primes (*drak*) and substituted-letter primes (*dcek*) share the same number of matching 'slots' with the target word (*dark*), and thus fail to explain the difference between both conditions. Wickelcoding theories also fail to account for this difference, because they assume that transposed-letter and substituted-letter primes share the same number of Wickelfeatures with the target (i.e. *drak* and *dark*, as well as *dcek* and *dark*, do not have any common Wickelfeatures). Open-bigram theories and Spatial Coding theories, on the other hand, provide theoretical frameworks that can successfully account for transposed-letter similarity effects. Open-bigram theories predict a greater degree of similarity between transposed-letter nonword and corresponding real word than between substituted-letter nonword and corresponding real word, due to the greater number of shared open-bigrams (i.e. *drak* and *dark* share three bigrams *da, dk, rk*, whereas *dcek* and *dark* only share one bigram *dk*), which is thus in line with the transposed-letter similarity hypothesis. Spatial Coding theories assume that the spatial codes of two letter strings sharing the same letter identities in different letter positions (*drak* versus *dark*) are more similar than the spatial codes of two letter strings with different letter identities (*dcek* versus *dark*).

Taken together, both Open-bigram and Spatial Coding theories can account for evidence from monomorphemic transposed-letter priming studies (see Davis & Bowers, 2003, for further discussion). But can these two theories also successfully account for evidence of position-specific morpho-orthographic processing (Christianson et al., 2005; Crepaldi, Rastle et al., 2010b; Duñabeitia et al., 2007) and position-independent morpho-orthographic processing (e.g. Crepaldi, Rastle et al., 2010a; Duñabeitia, Laka et al., 2009)?

With respect to position-independent compound-constituent processing, both Open-bigram theories and Spatial Coding theories handle the existing pattern of data well. Both coding strategies assume that the processing of a word's morpho-orthographic sub-constituents is possible even if the position of these constituents is reversed. According to Open-bigram Coding theories, the reversed compound nonword *moonhoney* activates the word *honeymoon*, because the open-bigrams of *moon* and *honey* are present in both *moonhoney* and *honeymoon*. According to Spatial Coding theories, the letter position coding system will try to find an existing match for the whole-letter string *moonhoney*. Given that such match does not exist, the system will try to shift the sub-constituents until an appropriate match is found (see Davis, 2010). Davis (2010) refers to a method called "Superposition Matching" which tries to match a given input letter string with an existing representation in the mental lexicon. The superposition function allows the shifting of constituents and thus a tool for the position-independent identification of lexical sub-structures. Superposition matching is a complentary function in the Spatial Coding system which operates simultaneously. That is, the morphemic constituent *moon* will be shifted into word final position or the morphemic constituent *honey* will be shifted into word initial position in order to find a correct lexical match.

However, with respect to position-specific morpho-orthographic processing, Open-bigram and Spatial Coding theories have more difficulty explaining the existing pattern of data. Christianson et al. (2005) and Duñabeita et al. (2007) have reported that morphologically complex words with letter transpositions across the morpheme-boundary (*walekr*) produce less priming than morphologically complex words with letter transpositions within the stem morpheme (*wlaker*). These findings challenge Open-bigram Coding theories, as they predict that morphologically complex words with within-morpheme and across-morpheme boundary transpositions share the same number of open-bigrams with their corresponding baseword (*wlaker* activates the open-bigrams *wl, wa, wk, we, wr,* ***la****, lk, le, lr, ak, ae, ar, ke, kr, er*, *walekr* activates *wa, wl, we, wk, wr, al, ae, ak, ar, le, lk, lr,* ***ek****, er, kr*, and *walker* activates *wa, wl, wk, we, wr, al, ak, ae, ar, lk, le, lr, ke, kr, er*). Open-bigram theories would thus predict equal magnitudes of priming for both within-morpheme and across-morpheme boundary transpositions, which is not the case. Similarly, Spatial Coding theories fail to account for these findings, because *wlaker* and *walekr* both equally produce an excellent match to the underlying whole-word string *walker*.

Another critical finding that challenges current theories of letter position coding is the absence of morpheme interference effects for nonwords comprising prefixes in final word position (*trustdis*) or suffixes in initial word position (*ingtrust*; Crepaldi, Rastle, & Davis, 2010). According to Open-bigram Coding theories the nonwords *trustdis* and *ingtrust* both equally match the word *trust*, because the bigrams *tr, tu, ts, tt, ru, rs, rt, us, ut*, and *st* are present in both letter strings. Similarly, Spatial Coding theories fail to account for position-specific effects of affix encoding, because they would predict that orthographic sub-constituents of the whole letter string can be shifted with respect to their position in the letter string. Hence, according to the Spatial Coding scheme, *trustdis* should activate *distrust* and *ingtrust* should activate *trusting*, which is inconsistent with the pattern of data reported by Crepaldi, Rastle, & Davis (2010b).

In summary, although both Open-bigram and Spatial Coding theories (C. J. Davis, 2010; Grainger & van Heuven, 2003) acknowledge that letters at initial or final position are coded with greater specificity than internal letters (Johnson et al., 2007; Perea & Lupker, 2007; Rayner et al., 2006), these models do not incorporate position-specific constraints for affixal units at initial or final positions, and therefore fail to account for position-specific morpho-orthographic priming effects (Christianson et al., 2005; Crepaldi, Rastle et al., 2010b; Duñabeitia et al., 2007).

Summary and research aims

Two key mechanisms underlying morphological processing during reading have been identified, one that uses orthographic constraints, and another that uses semantic constraints to analyse morphological structure. Both mechanisms have found broad acceptance in the field (e.g. Diependaele et al., 2009; McCormick et al., 2008, 2009; Meunier & Longtin, 2007; Rastle & Davis, 2008) and two main classes of theories have been formulated that can account for both mechanisms.

While form-then-meaning accounts propose that initial stages of morpho-orthographic decomposition are followed by later morpho-semantic processing stages, parallel dual-route theories predict that morpho-orthographic and morpho-semantic decomposition occurs simultaneously via two parallel processing routes. These conflicting theories open up important questions regarding the time-course and interplay of morpho-orthographic and morpho-semantic processing mechanisms.

One critical issue that arises is at what stage in word recognition access to the representation of the whole-word can be achieved. Form-then-meaning accounts consider that whole-word representations can only be activated indirectly via their morphemic sub-constituents (e.g. Crepaldi, Rastle, Coltheart et al., 2010), therefore morphological decomposition is a necessary premise for whole-word recognition. Parallel dual-route models propose that whole-word representations are directly available at initial word processing stages (e.g. Diependaele et al., 2009), therefore morphological decomposition is not necessarily needed for whole-word recognition. Chapter 2 addresses this question, comparing truly suffixed (*darkness*) and pseudo-suffixed words (*glossary*) with within-boundary (*d**ra**kness/g**ol**ssary*) to across-boundary (*dar**nk**ess/glos**as**ry*) letter transpositions. The logic here is that if orthographic alterations of the morphemic boundary disrupt complex word recognition, it can be followed that the reading system greatly relies on a morphological parsing route. If, however, such disruption does not occur, then there must be an alternative direct pathway to the representation of the whole-word, which enables the morphological processing system to recover from morpheme-boundary manipulations.

A second related research question is at what stage in morphological processing semantic influences begin to play a role. While form-then-meaning accounts propose that influences of semantics should occur *late*, parallel dual-route accounts suggest that morpho-semantic information is processed *early*. To address the degree to which morphological processing relies on semantic relatedness, it is essential to compare words in which there is no semantic relationship between the stem and the whole-word (e.g. *moth-er, gloss-ary*, etc.) to those in which there is a semantic relationship (e.g. *gold-en, teach-er*, etc.). A major focus of this thesis is therefore to carefully study different degrees of semantic relatedness in different types of morphologically structured letter strings and to test how early in morphological processing semantic transparency effects first begin to emerge. This question is addressed in Chapter 2 and 4 of the present thesis.

Other research questions arise particularly with respect to the nature of morpho-orthographic processing system. Morpho-orthographic decomposition is by now known to be one of the most fundamental and best-replicated cognitive mechanisms for rapid subconscious morphological analysis during reading (Longtin & Meunier, 2005; Longtin et al., 2003a; McCormick et al., 2008, 2009; Rastle & Davis, 2008). However, although current morphological processing theories have benefited enormously from such major empirical advances, they are yet not well developed. Current morpho-orthographic processing theories agree that morphologically complex words are decomposed at the morpheme boundary into orthographically defined morphemic units, independently from semantics (Longtin & Meunier, 2005; Rastle et al., 2004). But relatively little is still known as to when exactly morpho-orthographic decomposition occurs and how precisely morpho-orthographic units are decoded during reading.

A fundamental limitation of previous research is that letter transpositions have primarily been studied in the context of truly affixed words (e.g. Christianson et al., 2005; Duñabeitia et al., 2007; Rueckl & Rimzhim, 2010). The one study that has investigated letter transpositions in pseudo-affixed words (Christianson et al., 2005) was done on a small set of 10 items, using one single suffix *er*, and was lacking statistically convincing results. It therefore remains uncertain whether position-independent morphological encoding only applies to truly affixed words or if it can also be found in pseudo affixed words and affixed nonwords. Future research thus needs to be followed up by systematic comparisons of transposed-letter similarity effects in morphological processing in different types of complex words (truly affixed, pseudo-affixed, non-affixed, affixed nonwords, etc.). Affixed nonwords, particularly, make a strong case, because they are not lexically represented in the reading system and are semantically rather poorly defined. They therefore provide significant grounds for investigations of a purely form-based type of morphological decomposition, which we examine in Chapter 3 and 4, in both English and Spanish.

Previous research has also yielded ambiguous results regarding letter transpositions at morpheme boundaries. While some evidence suggests that transposed-letter similarity effects disappear for across-boundary transpositions (Christianson et al., 2005; Duñabeitia et al., 2007), other evidence report the presence of across-boundary transposed-letter similarity effects (Perea & Carreiras, 2006; Rueckl & Rimzhim, 2010). A direct and systematic comparison of stem-internal letter transpositions versus across-boundary transpositions is therefore a central aim for future research, which we address in Chapter 2.

More generally, it is still not understood to date how exactly morpho-orthographic representations are positionally defined. Does the letter position coding system uniquely operate on basis of matching input letter strings onto matching lexical entries, or is there an additional mechanism that allows the decoding and stripping of affixal sequences at the same time at which the letter position coding system is still trying to produce a suitable match? Chapter 3 examines this question by investigating transposed-letter priming effects in suffixed transposed-letter nonwords (*wranish-WARN*) relative to non-suffixed transposed-letter nonwords (*wranel-WARN*). And what degrees of positional specificity are present at the time that morpho-orthographic processing occurs? Chapter 4 tests in which ways the morphological parsing system is challenged by transposed-letter manipulations, by systematically comparing complex transposed-letter nonwords (*wlaker-WALK*) to their morphological related counterparts (*walker-WALK*).

Finally, Chapter 5 provides some first insights into the development of morphological processing mechanisms in young children. Despite the extensive body of research in adults, the evidence on morphological processing in developing readers is still surprisingly sparse. Work from developmental research provides an important window to structure and processing mechanisms of the human reading system. However, models of reading development are still underspecified. This makes it difficult to assess morphological knowledge in young readers and to use developmental insights to inform cognitive models of the adult reading system. Important research questions thus still remain, as to a) *when* in reading development children first establish an automatic morphological parsing system, and b) *how* exactly morphological knowledge is acquired. Chapter 5 reports evidence from two groups of developing readers (Year 3 and Year 5) examining (i) at what age in reading development morpho-orthographic processes are acquired and (ii) the strategies that young readers use to acquire morphological knowledge.

Thesis summary and conclusions are presented in a final chapter and possible future directions are discussed. Our research furthers the understanding of how words are processed in the adult and in the developing brain and thus informs theoretical models of morphological processing, demonstrating that understanding the mechanisms involved in language processing and language acquisition are of great practical relevance as well as theoretical interest.

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Parallel processing of whole-words and morphemes in visual word recognition

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Abstract

Models of morphological processing make different predictions about whether morphologically complex written words are initially decomposed and recognised on basis of their morphemic subunits or whether they can directly be accessed as whole words and at what point semantics begin to influence morphological processing. In this study, we used unprimed and masked primed lexical decision to compare truly suffixed (*darkness*) and pseudo-suffixed words (*glossary*) with within-boundary (*d**ra**kness/g**ol**ssary*) to across-boundary (*dar**nk**ess/glos**as**ry*) letter transpositions. Significant transposed-letter similarity effects were found independently of the morphological position of the letter transposition, demonstrating that, in English, morphologically complex whole-word representations can be directly accessed at initial word processing stages. In a third masked primed lexical decision experiment, the same materials were used in the context of stem-target priming and it was found that truly suffixed primes facilitate the recognition of their stem target (*darkness-DARK*) to the same extent as pseudo-suffixed primes (*glossary-GLOSS*) which is consistent with theories of early morpho-orthographic decomposition. Taken together, our findings provide evidence for both whole-word access and morphological decomposition at initial stages of visual word recognition and are discussed in the context of a hybrid account.

Keywords: visual word recognition, whole-word processing, morphological decomposition, lexical decision, letter transpositions

Parallel processing of whole-words and morphemes in visual word recognition

Many decades of research have been directed towards understanding whether morphologically complex printed words like *darkness* are decomposed and accessed on the basis of their morphemic subunits during reading (e.g. Taft & Forster, 1975) or retrieved through a direct whole-word access route (e.g. Burani & Caramazza, 1987; Burani & Laudanna, 1992; Caramazza et al., 1988). In recent years, an increasing body of evidence, across several languages, has been amassed favouring a decomposition account (Deutsch et al., 1998 [Hebrew]; Diependaele et al., 2005 [Dutch and French]; Drews & Zwitserlood, 1995 [Dutch and German]; Duñabeitia et al., 2007 [Spanish and Basque]; Frost et al., 1997 [Hebrew]; Longtin & Meunier, 2005 [French]; Rastle et al., 2004 [English]). Questions remain, however, as to exactly when morphologically complex words are decomposed and as to whether complex word recognition uniquely relies on morpheme-based access or whether whole-word representations are also simultaneously available at early recognition stages. The aim of the present research was (1) to investigate whether morphologically complex whole-words are always accessed on basis of their morphemic form units or if there is a direct pathway to the full form representations which are then subsequently decomposed, or both, and (2) to test at what point semantics begins to influence morphological processing.

Current theories of morphological processing can be summarized in terms of four main approaches. The first approach considers that morphologically structured words are automatically decomposed into their morphemic subunits which then in turn activate the lexical representation of the whole-word (Taft, 1994, 2003). This *obligatory decomposition account* therefore proposes that the analysis of morphologically complex words can solely be attained through prelexical parsing of the letter string into morphemes. Such a pre-lexical mechanism is regarded as being semantically 'blind', in that the parsing process uniquely relies on the orthographic characteristics of the morphemes (*morpho-orthographic decomposition*) and decomposes any letter string with the mere appearance of morphological complexity (e.g. *darkness* but also *glossary*).

Secondly, a *supralexical account* of morphological decomposition has been proposed, according to which the decomposition of a letter string occurs only after the whole-word has been accessed in the lexicon (Giraudo & Grainger, 2001; H. Giraudo & J. Grainger, 2003). The morphemic representations then in turn activate higher-level semantic representations, which send back activation to corresponding form representations. This account thus differs from the obligatory decomposition approach in that morphological decomposition involves a semantically-based search for morphemes (*morpho-semantic decomposition*), which is only successful for true morphological structures (i.e. *darkness* but not *glossary*).

The third and fourth approaches are based on the assumption that morphological decomposition does not exclusively rely on one single segmentation mechanism. The third approach considers that morphological decomposition is triggered initially by a purely orthographic type of analysis and subsequently by a decomposition mechanism relying on the syntactics of a word (Crepaldi, Rastle, Coltheart & Nickels, 2010). The model resembles the obligatory decomposition account in that both propose that morphologically complex words are always initially recognized on the basis of semantically-independent decomposition at prelexical stages in visual word recognition (Longtin & Meunier, 2005; McCormick et al., 2008, 2009; Rastle et al., 2004). However, in contrast to the obligatory decomposition account, the initial morpho-orthographic processing stage is followed by a lemma level at which inflected word forms (e.g. *cats*, *fell*, etc.) are mapped onto their infinitives (e.g. *cat*, *fall*, etc.), which are then later mapped onto the semantic level. We will therefore refer to this approach as the *form-then-meaning account* (see Figure 1, Panel C).

Note that a related form-then-meaning approach has been proposed suggesting that the initial parsing of whole words into morpho-orthographic subunits is followed by a later morpho-semantic processing stage (e.g. Meunier & Longtin, 2007; Rastle & Davis, 2008). This model, however, is not depicted in Figure 1, as it makes no explicit predictions at to whether (i) morpho-semantic processing operates pre-lexically or post-lexically and (ii) if it involves the *decomposition* into morphemes or rather tests the *recombination* of morphemic representations such that a meaning is generated if two morphemic units successfully recombine (as in the case of *dark* and *ness*).

Fourth, the *hybrid model* postulates parallel mapping onto both prelexical form representations and supralexical semantically dependent representations (Diependaele et al., 2009; see also Feldman et al., 2009). It explicitly claims that morphologically complex words are listed in the lexicon, such that morphemes do not necessarily mediate access to the whole-word form. In contrast to the form-then-meaning account, morpho-orthographic and morpho-semantic decomposition can occur in parallel at early initial processing stages in visual word recognition.

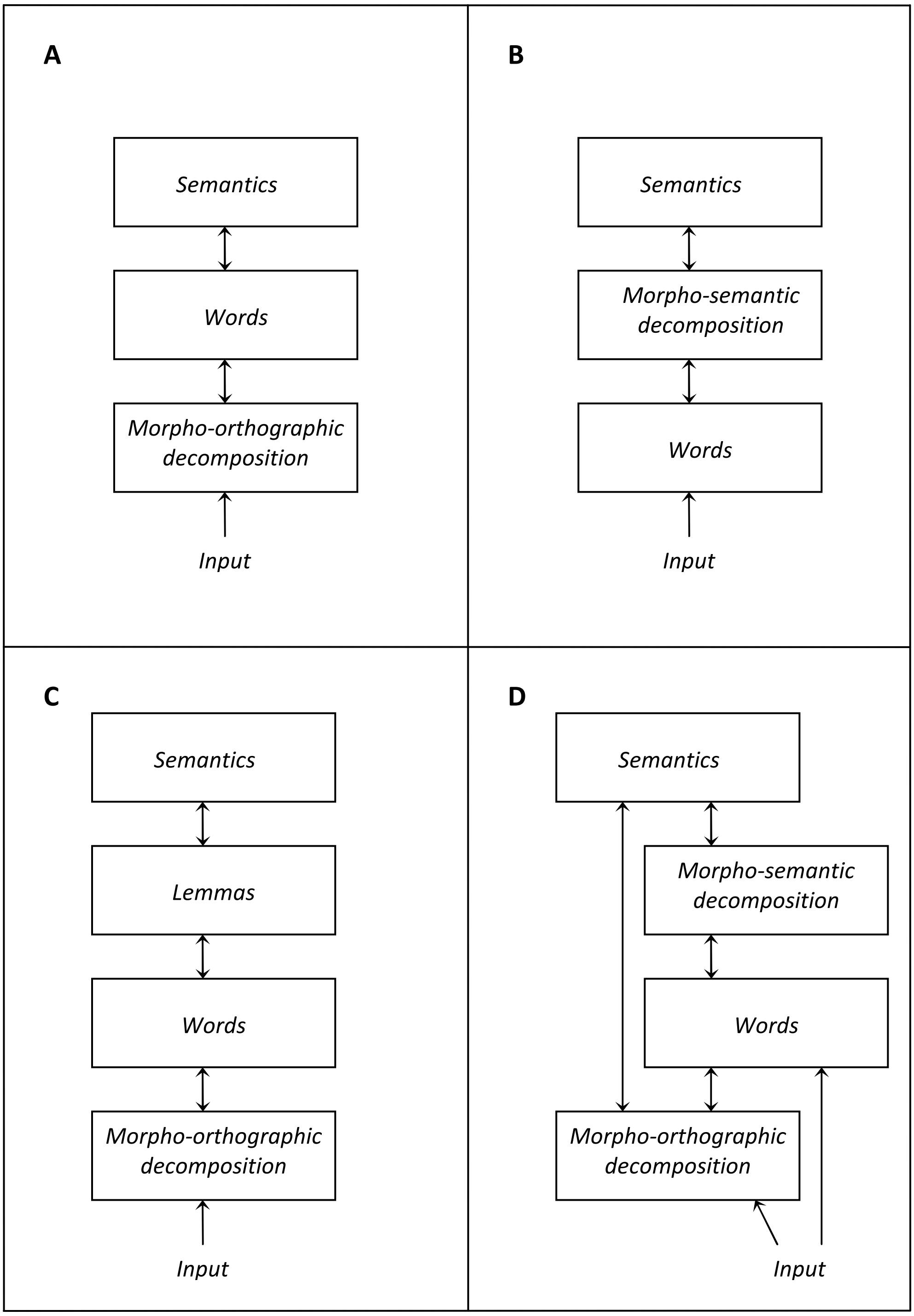

Figure 1. Figure 1 describes four different morphological processing accounts. Panel A refers to the obligatory decomposition account (Taft, 2003), panel B to the supralexical account (Giraudo & Grainger, 2001), panel C to the form-then-meaning account (Crepaldi et al., 2010) and panel D to the hybrid model (Diependaele et al., 2009).

The goal of the present research was to provide data to adjudicate between these accounts by (i) exploring whether or not morphologically complex words are directly accessed as whole units at initial word processing stages and (ii) exploring when semantic information begins to affect morphological processing.The accounts split into two main camps on these questions. While the supralexical account and the hybrid model propose that (i) there *is* a direct pathway to the lexical representations of full forms and that (ii) morpho-semantic information is processed *early* (Figure 1, Panel B and D), the obligatory decomposition account and the form-then-meaning account consider that (i) there *is no* direct pathway, since morpho-orthographic subunits are always used to access the full form and that (ii) influences of semantics should occur *late* (Figure 1, Panel A and C).

To this end, we conducted experiments drawing on the well-known *transposed-letter similarity effect*. Transposed-letter similarity effects reflect the high degree of similarity between a transposed-letter (TL) nonword (*d**ra**k*) and its corresponding baseword (*dark*) relative to a substituted-letter control (*d**ce**k*) and are accounted for by models of orthographic encoding that assume imprecise initial coding of letter positions at early stages of word processing (Gómez, Ratcliff, & Perea, 2008; Grainger & van Heuven, 2003). As a consequence of the imprecise position encoding of the letters in a TL-nonword like *d**ra**k*, the system will activate the closest pattern matching the misspelled input (*dark*).

To address our first research question of whether whole-words are directly accessed at initial word recognition stages, we manipulated morphologically complex words in two different ways: firstly, by transposing two adjacent letters *within* the stem morpheme (*d**ra**kness*; maintaining the suffix *ness* as a morphological parsing unit) and secondly, by transposing two adjacent letters *across* the boundary between stem morpheme and suffix (*dar**nk**ess*; disrupting the suffix as a morphological unit), following the recent work of several researchers (Christianson, Johnson & Rayner (2005; Duñabeitia, Perea & Carreiras, 2007; Perea & Carreiras, 2006; Rueckl & Rimzhim, 2010). If it is true that morphologically complex words can be directly accessed as whole units, as proposed by the supralexical account and the hybrid model, no parsing into morphemes should be necessary and the disruption of across morpheme-boundary transpositions should therefore not interfere with the recognition process. Hence, the transposed-letter effect would be expected to arise for both within-boundary (*d**ra**kness*) and across-boundary transpositions (*dar**nk**ess*). If it is the case, however, that morphemes are used as access units to the representation of the whole-word, as predicted by the obligatory decomposition account and the form-then-meaning account, the morphological parser will try to match input strings with underlying morphological sub-structures (*dark* + *ness*). A disruption of morphological form structures through across-boundary transpositions (*dar**nk**ess*) would therefore inhibit the morphological parsing of the letter string, leading to the weakening of the transposed-letter effect for across morpheme boundary transpositions.

Previous masked priming studies investigating across-morpheme boundary transpositions have provided conflicting results. Firstly, Christianson et al. (2005) found evidence for the disappearance of transposed-letter priming across morphemes in both derivationally suffixed words (*boas**et**r-BOASTER*) and compounds (*sil**wk**orm-silkworm*), using a masked primed naming task in English. Similarly, a related masked primed lexical decision study in Spanish and Basque by Duñabeitia et al. (2007) revealed that prefixed and suffixed words with within-morpheme boundary transpositions (*meosnero-MESONERO* [*brakeeper-BARKEEPER*]) produced significant TL-priming, whereas no priming was obtained when letters were transposed across the morpheme boundary (*mesoenro-MESONERO* [*bakreeper-BARKEEPER*]). Recently, however, these findings have been challenged by a set of masked priming lexical decision experiments conducted by Rueckl and Rimzhim (2010), in English. Robust TL-priming was found for both within-boundary and across-boundary transpositions, independently of whether the presented targets were stems (*tea**hc**er-TEACH*) or whole-words (*tea**hc**er-TEACHER*). Likewise, Pereas & Carreiras (2006) carried out a masked primed lexical decision study using Basque compound words and found that the transposed-letter priming effect did *not* decrease for across morpheme boundary transpositions.

Hence, while Rueckl and Rimzhim's and Perea and Carreiras' findings suggest that there *is* a direct access route to the representations of the whole-word, Christianson et al. and Duñabeitia et al.'s results suggest that there *is not*. Given this considerable inconsistency in previous findings, we first aimed at replicating Rueckl and Rimzhim's findings by adapting this approach in a set of experiments in English (see Table 1).

Table 1. *Target words used in Experiment 1.*

	TL within	SL within	TL across	SL across
truly suffixed	d**ra**kness	d**ce**kness	dar**nk**ess	dar**vb**ess
pseudo-suffixed	g**ol**ssary	g**it**ssary	glos**as**ry	glos**et**ry
non-suffixed	c**sa**hew	c**ri**hew	cas**eh**w	cas**if**w

In addition, critical to our second research question, we included a pseudo-suffixed condition which allowed us to explore the degree to which visual word recognition processes rely on the morpho-orthographic parsing system in words in which there is no semantic relationship between the stem and the whole-word (*gloss* + *ary*). Words were manipulated by transposing letters within and across the pseudo-morpheme boundary. Again, morphological processing accounts make different predictions about the pattern of priming effects here. While the supralexical account and the hybrid model would predict a transposed-letter effect to arise for within pseudo-boundary (*g**ol**ssary*) and across pseudo-boundary (*glos**as**ry*) transpositions, the obligatory decomposition and form-then-meaning accounts would propose the weakening of the transposed-letter similarity effect for across-boundary transpositions. Most critically however, due to the semantically opaque nature of pseudo-suffixed items, models proposing an early onset of morpho-semantic priming effects (i.e. the supralexical account and the hybrid model) predict that the reading system prioritizes the processing of semantically transparent structures, resulting in an increased transposed-letter similarity effect for truly suffixed as compared to pseudo-suffixed words. In contrast, the obligatory decomposition account and the form-then-meaning account postulate a late onset of morpho-semantic processing and would thus predict no difference between truly and pseudo-suffixed transposed-letter similarity effect.

Christianson et al. (2005) are the only researchers to date to have tested across-boundary transpositions in pseudo-suffixed words using a masked primed naming task. They showed that, while transposed-letter priming disappeared in the truly suffixed across-boundary condition (*boas**et**r-BOASTER*), the pseudo-suffixed condition revealed evidence for across-boundary transposed-letter priming (*blus**et**r-BLUSTER*) indicating that transposed-letter priming effect did *not* decrease for pseudo-boundary transpositions. Unfortunately however, Christianson et al.'s study used only 12 pseudo-suffixed items and was constrained to one single suffix *–er*, which makes it difficult to generalize their findings. In addition, the critical interaction with truly suffixed priming was not significant, rendering their findings somewhat inconclusive. A further limitation is that Christianson et al. did not compare across-boundary to within-boundary transpositions, which provides a critical control for the degree of impact through boundary disruption. In our present studies, we used a set of 40 pseudo-suffixed items with 13 different suffixes, and carried out both within and across-boundary transpositions, thus providing an important extension of this research.

A non-suffixed control condition (*cashew*) incorporating an existing morpheme (*cash*) and a meaningless non-morphemic ending (*ew*) was employed in the present experiments to guarantee that the observed effects were not simply due to orthographic overlap. This is a critical control condition, which has not been included in previous transposed-boundary studies in English (i.e. Christianson et al., 2005 and Rueckl & Rimzhim, 2010). Given that non-suffixed letter strings are fully represented in the lexicon, a significant transposed-letter effect would be expected to arise independently of the position of letter transposition (*c**sa**hew*/*cas**eh**w*).

In the first experiment, we used a basic lexical task, namely unprimed lexical decision. Typically, in a lexical decision task participants are slower to respond 'no' to a transposed-letter nonword like *d**ra**k* relative to an orthographic control like *d**ce**k* (e.g. Andrews, 1996). In the second and third experiments, we extended the research to investigations of masked primed lexical decisions.

Experiment 1

Method

Participants

Forty-eight undergraduate and graduate students participated in this study for course credit or monetary reimbursement. All participants were native English speakers.

Materials

A set of 120 words was selected from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993): 40 truly suffixed (*darkness*), 40 pseudo-suffixed (*glossary*), and 40 non-suffixed items (*cashew*). The words of each set were matched listwise on logarithmic whole-word frequency (mean log frequency of 0.69), logarithmic stem frequency (mean log frequency of 1.17), length (mean length of 6.7 letters) and orthographic N (mean N of 0.8). In the truly suffixed condition, the meaning of the whole-word could be derived from the meaning of the stem (*dark*) and the syntax of the suffix (*ness*). As opposed to the truly suffixed condition, the pseudo-suffixed words were chosen such that their meaning could not be derived from the meaning of its morphemic subunits (*gloss* + *ary*). The non-suffixed controls shared the first letters with another existing letter string (*cash*) followed by a non-morphemic ending (*ew*).

For each word we created two TL-nonwords by transposing two adjacent letters either within the stem or across the morpheme boundary. The transpositions within the stem were always performed at position 2-3 (e.g. *d**ra**kness*, *g**ol**ssary*, *c**sa**hew*, etc.), whereas in the across-conditions the TL-position varied with the length of stem morpheme (e.g. *dar**nk**ess*, *glos**as**ry*, *cas**eh**w*, etc.). Letter transpositions included either two consonants (*o**gr**anist*), two vowels (*d**ei**tary*), or one consonant and one vowel (*b**lu**bous*). The within- and across-conditions were matched on the number of C-C, V-V and V-C transpositions, on position specific bigram frequency, syllable structure, and on orthographic neighbourhood size (N). The within-morpheme transpositions occurred exclusively at internal letter positions. The nonword stimuli were partly pronounceable and partly unpronounceable nonwords. We controlled this factor across conditions. Appendix 1 provides a complete listing of the test stimuli used.

For each item type, 40 TL-within nonwords and 40 TL-across nonwords were constructed (240 TL-nonwords in total). SL-nonwords were created by substituting the transposed-letters with two new letter identities (vowels with vowels and consonants with consonants). Four lists were created, so that each target only appeared once in each list. Twelve participants were randomly assigned to each of the lists.

For the purpose of the lexical decision task, we included a set of 120 word targets. These were matched with the TL-basewords (*darkness*, *glossary*, *cashew*, etc.) on logarithmic frequency (range: 0-2.4, mean value: 0.72), length (range: 6-9, mean value: 6.86) and orthographic N (range: 0-10, mean value: 0.66). Each filler word was either truly suffixed (*agreeable*), pseudo-suffixed (*apartment*) or non-suffixed (*arcade*). In addition, 20 monomorphemic practice stimuli were selected.

Procedure

The experiment was run on PCs with CRT monitors, and stimuli presentation and data collection were controlled with DMDX (Forster & Forster, 2003). Each participant was tested individually in a quiet room. Targets were presented in lowercase on a computer screen and remained on the screen until the subject responded or for a maximum of 3000 ms and the next trial was presented immediately after target offset. Participants were asked to decide as quickly and accurately as possible whether the visually presented items were real English words or not. The trials were presented in four blocks, with participants receiving three breaks in the middle. All stimuli were presented in a randomized order within presentation blocks. Each experimental session lasted for about 10 minutes.

Results

No outlier subjects were discarded as error rates for every subject were below 30%. Moreover, neither standard-deviation trimming (discarding reaction times above or below 3.0 SDs each participants mean reading time), nor absolute-value trimming (using 300 ms as a low cut-off and 1500 ms as a high cut-off) changed the size and the direction of the main effects and interactions. Mean reaction times (RT) and error rates (ER) were analysed for each subject and are presented Table 2.

Table 2. *Table 2 presents mean lexical decision times and error rates for word targets averaged across subjects in Experiment 1. Standard deviations are shown in parentheses.*

Condition		Reaction times	Error Rates	Example
Truly suffixed				
TL-within		756 (228)	11.7 (13.4)	d**ra**kness
SL-within		689 (211)	4.0 (7.4)	d**ce**kness
	TL-effect	67	7.7	
TL-across		807 (234)	8.1 (11.4)	dar**nk**ess
SL-across		690 (214)	1.9 (4.5)	dar**vb**ess
	TL-effect	117	6.2	
Pseudo-suffixed				
TL-within		682 (215)	6.3 (9.6)	g**ol**ssary
SL-within		668 (198)	1.5 (4.6)	g**it**ssary
	TL-effect	14	4.8	
TL-across		712 (194)	8.1 (10.7)	glos**as**ry
SL-across		672 (192)	2.9 (5.4)	glos**et**ry
	TL-effect	40	5.2	
Non-suffixed				
TL-within		700 (178)	7.7 (10.4)	c**sa**hew
SL-within		636 (191)	2.5 (4.4)	c**ri**hew
	TL-effect	64	5.2	
TL-across		794 (254)	16.5 (16.4)	cas**eh**w
SL-across		684 (202)	2.1 (5.0)	cas**if**w
	TL-effect	110	14.4	

Response latencies were transformed logarithmically and the main analyses were performed using linear mixed effect model modelling (e.g. Baayen, 2008; Baayen, Davidson, & Bates, 2008). To reduce the variance in the models, we included the predictor Trial Number as a measure of how far participants had progressed into the experiment, allowing control for longitudinal task effects such as fatigue or habituation. Only those fixed effects and random effects are presented below that significantly improved the model's fit in a stepwise model selection procedure. For each Item Type (Truly Suffixed, Pseudo-suffixed, Non-suffixed) and Position (Within, Across), a separate generalised linear mixed-effects model as implemented in the lme4 package (from http://cran.r-project.org/web/packages/) in the statistical software R (version 2.10.1, RDevelopmentCoreTeam, 2008) was created with two fixed effects factors (Trial Number and TL-Status: Transposed-letter, Substituted-letter) and two random-effects factors (random intercepts for Subjects and Items). Significance was assessed with p-value sampling *pvals.fnc*, as implemented in the language R package (Baayen, 2008).

The models revealed that truly suffixed TL-within nonwords (***dra**kness*) were responded to significantly slower (by 67 ms) than their corresponding SL-controls, t = 2.34, p = .019 (i.e. transposed-letter effect, hereafter). Similarly, a significant transposed-letter effect was also observed for truly suffixed TL-across nonwords (*dar**nk**ess*; 117 ms), t = 5.99, p < .001. The results further revealed that pseudo-suffixed TL-within nonwords (*g**ol**ssary*) did not differ significantly (14 ms) from their SL-controls. However, in the pseudo-suffixed across-condition (*glos**as**ry*), a significant transposed-letter effect was obtained (40 ms), t = 2.46, p = .014. Finally, in the Non-suffixed conditions, both TL-within (64 ms; t = 2.26, p = .024) and TL-across (110 ms; t = 5.0, p < .001) manipulations yielded a significant transposed-letter effect.

To further explore the transposed-letter effect sizes within as compared to across the boundary, we performed three separate analyses for each Item Type using a generalised linear mixed-effects model with four fixed effects factors (Trial Number, TL-Status: Transposed-letter, Substituted-letter; Position: Within, Across and interaction between TL-Status and Position) and two random-effects factors (random intercepts for Subjects and Items). There was a significant main transposed-letter effect in the truly suffixed condition, t = 5.01, p < .001, in the pseudo-suffixed condition, t = 2.22, p = .027, and in the non-suffixed condition, t = 4.59, p < .001. There was also a significant main effect of Position in the non-suffixed condition, t = 2.03, p = .042, however the interaction of TL-Status and Position was not significant, t = 1.52, p = .128.

In addition, for the purpose of directly comparing effect sizes between item types, we performed three separate pair-wise comparisons using generalised linear mixed-effects model with eight fixed effects factors (Trial Number, TL-Status: Transposed-letter, Substituted-letter; Position: Within, Across; Item Type: Truly Suffixed, Pseudo-suffixed/Truly Suffixed, Non-suffixed/Pseudo-suffixed, Non-suffixed; interaction of TL-Status and Position; interaction of TL-Status and Item Type; interaction of Position and Item Type; and interaction of TL-Status; Position and Item Type) and two random-effects factors (random intercepts for Subjects and Items). The truly and pseudo-suffixed data revealed a significant interaction between Item Type and TL-Status, t = 2.25, p = .025. No other interactions were significant.

Finally, to test the overall pattern of results, we collapsed across Item Type and a generalised linear mixed-effects model was used with four fixed effects factors (Trial Number, TL-Status: Transposed-letter, Substituted-letter; Position: Within, Across and interaction between TL-Status and Position) and two random-effects factors (Subjects and Items). The data revealed a significant transposed-letter effect across all item types, t = 6.55, p < .001. Moreover, a significant interaction between Prime Type and Position revealed that there was a significantly larger transposed-letter effect in the across conditions than in the within conditions, t = 2.22, p < .027. The main effect of Position was not significant.

The error analyses were performed following the analyses used in the response latency data. These analyses revealed a robust transposed-letter effect for both truly suffixed TL-within nonwords (7.7%), t = 2.75, p = .006, and truly suffixed TL-across nonwords (6.2%), t = 3.51, p < .001. A significant transposed-letter effect was also observed for pseudo-suffixed TL-within nonwords (4.8%), t = 3.40, p < .001, and pseudo-suffixed TL-across nonwords (5.2%), t = 2.45, p = .015. Similarly, in the non-suffixed conditions, both TL-within nonwords (5.2%; t = 2.25, p = .025) and TL-across nonwords (14.4%, t = 5.31, p < .001) yielded a significant transposed-letter effect. The effects in the real word filler data were not significant.

The error analyses for each Item Type revealed a significant main transposed-letter effect in the truly suffixed condition, t = 2.67, p = .008, in the pseudo-suffixed condition, t = 2.82, p = .005, and in the non-suffixed condition, t = 5.81, p < .001. In the non-suffixed condition there was also a significant interaction of TL-Status and Position, t = 2.62, p = .009. The pair-wise comparison revealed a significant interaction of TL-Status and Position, when analysed across truly and non-suffixed trials, t = 2.68, p = .007, and when analysed across pseudo and non-suffixed trials, t = 2.96, p = .003, indicating that there was a significantly stronger transposed-letter similarity effect in the non-suffixed than in the truly and pseudo-suffixed condition. There was also a significant three-way interaction of Item Type, TL-Status and Position when analysed across truly and non-suffixed trials, t = 2.62, p = .009, and when analysed across pseudo and non-suffixed trials, t = 2.00, p = .046, indicating that there was a position-effect in the non-suffixed error data which was not present than in the truly and pseudo-suffixed condition. When collapsed across all Item Types, there was a significant transposed-letter effect of error, t = 7.71, p < .001. No other effect was significant.

Discussion

Experiment 1 was designed to test the size of transposed-letter similarity effects obtained with truly suffixed and pseudo-suffixed words with within-boundary (*d**ra**kness*/*g**ol**ssary*) and across-boundary (*dar**nk**ess*/*glos**as**ry*) transpositions. The latency and accuracy data revealed a significant transposed-letter effect for truly suffixed words with within-boundary transpositions (*d**ra**kness*), and for non-suffixed words (*c**sa**hew*/*cas**eh**w*) independent of the position of letter transposition. In the pseudo-suffixed data, there was a numerical difference for within-boundary transpositions (*g**ol**ssary*) which only reached significance in the error data.

Most critically however, in line with Rueckl and Rimzhim (2010), a significant transposed-letter effect was obtained in cases in which letter transpositions crossed either a true morphemic boundary (*dar**nk**ess*) or a morphemic pseudo-boundary (*glos**as**ry*), as reflected in both latency and accuracy data, indicating that the transposed-letter effect was not disrupted by the transposition of morpheme boundary or pseudo-morpheme boundary letters. These findings are inconsistent with the hypothesis that the effects of TL-similarity are reduced for across-boundary transpositions in truly suffixed and pseudo-suffixed words and suggest that the processing of these words was not subject to the effects of a structurally-based morphological decomposition process.

The transposed-letter effects in the truly suffixed conditions were overall larger than in the pseudo-suffixed conditions which appears to suggest that base words in which stem and whole-word comprise a semantic relationship (*darkness*) are activated more strongly than when the relationship is semantically opaque (*glossary*). However, the difference between the truly and non-suffixed condition was not significant and also the between-condition comparisons were not modulated by the morphological manipulation of Position, making it difficult to draw a definite conclusion of an advantage for truly affixed items.

Interestingly, in the response latency data, TL-nonwords with letter transpositions within the stem morpheme (*d**ra**kness*, *g**ol**ssary*, *c**sa**hew*, etc.) were actually overall classified *faster* than TL-nonwords comprising a letter transposition across the morpheme boundary (dar**nk**ess, *glos**as**ry*, *cas**eh**w*, etc.). In the error data, a similar pattern was found in the non-suffixed condition, but not in the truly and pseudo-suffixed condition. By definition, within-stem transpositions occurred earlier in the letter string, i.e. at TL-position 2-3 (*f**er**ely*) and 3-4 (*bu**gr**lary*) than across-boundary transpositions, i.e. at TL-position 4-5 (*dar**ek**st*), 5-6 (*demo**in**c*), 6-7 (*symbo**il**c*), or 7-8 (*scratc**yh***). Therefore, it is possible that this effect was due to some kind of left-to-right checking strategy for the position of the letter transposition. To investigate this, we carried out a control experiment investigating the effect of position of letter transpositions. Using a matched set of monomorphemic stimuli, we compared early to late transpositions using unprimed lexical decision. The study revealed that TL-nonwords including letter transpositions at early positions in the letter string (*g**ol**be* vs. *g**ir**be*) were classified faster than TL-nonwords with late letter transpositions (*ma**gn**o* vs. *ma**ps**o*), which confirmed the hypothesis that response times in the present lexical decision task may have been affected by a left-to-right checking strategy for letter transpositions. Moreover, this effect was found for both legal (*g**ol**be/ma**gn**o*) and illegal bigrams (s**rt**ict/aro**rw**) suggesting a post-lexical locus of such left-to-right spelling check.

In summary, Experiment 1 constitutes two key findings. First, as mentioned above, the data confirm that a nonword which is a TL-version of a real word activates the lexical entry of that word independently of whether the transposition crosses a morphological boundary or not, producing a delay in the lexical decision response. This finding is critical, as it is consistent with the class of morphological processing theories that considers that morphologically complex words can be directly accessed as whole words, without prior decomposition, and inconsistent with the others. Second, the present data suggest that, once a lexical entry is activated, a spelling check is initiated with TL-nonwords, but not with SL-nonwords, and that such spelling check is done from left to right, as reflected by the speeded rejection of TL-nonwords with early within-transpositions relative to TL-nonwords with late across-transpositions. This second finding seems to reflect a mechanism which operates post-lexically over the misspelled input letter string and does therefore not affect the interpretation of the first result. We would thus predict that in a paradigm in which readers are unable to apply a left-to-right checking mechanism, such a position effect should be absent, while transposed-letter effects for within- and across-transpositions should both be present.

To avoid the use of such strategic checking mechanisms, we switched to a different paradigm in Experiment 2, namely masked priming. In a typical masked priming experiment, a forward mask is presented, followed by a briefly presented stimulus (the prime), which in turn is immediately replaced by another stimulus (the target). Participants are not aware of the existence of the masked prime, but its influence can still be measured on target recognition. The processing of the briefly presented prime (typically shown for 40-70 ms) is posited to reflect early, automatic processing stages (Forster & Davis, 1984; Forster, Davis, Schoknecht, & Carter, 1987).

The same transposed-letter targets of Experiment 1 (*d**ra**kness* and *dar**nk**ess*) were presented as masked primes in Experiment 2, followed by the corresponding real word targets (*drakness-DARKNESS* and *darnkess-DARKNESS*). As opposed to unprimed lexical decision in which the *transposed-letter similarity effect* is reflected by a delay in the NO-decision to the TL-nonword target, the *transposed-letter priming effect* in a masked priming paradigm is typically evidenced by a speeded YES-decision to the real word target. If it is true that morphologically complex words can be directly accessed as wholes at initial recognition stages, TL-priming should equally occur for within-boundary (*d**ra**kness/g**ol**ssary/c**sa**hew*) and across-boundary (*dar**nk**ess/glos**as**ry/case**eh**w*) transpositions. If, however, word recognition is based on a structural segmentation mechanism which blindly decomposes any complex letter string into morphemic subunits at initial word processing stages, transposed-letter priming should be present for truly suffixed and pseudo-suffixed within-boundary transpositions (*d**ra**kness/g**ol**ssary*) and non-suffixed words (*c**sa**hew/case**eh**w*), but diminished for across-boundary transpositions in truly suffixed (*dar**nk**ess*) and pseudo-suffixed words (*glos**as**ry*).

Moreover, if it is true that the reading system is sensitive to semantic factors at early processing stages, increased amounts of priming would be expected to occur in the truly suffixed relative to the pseudo-suffixed condition. If, however, early processing stages are semantically 'blind', a semantic transparency effect would not be expected.

Experiment 2

Method

Participants

Forty-eight undergraduate and graduate students participated in this study for course credit or monetary reimbursement. All participants were native English speakers.

Materials

The same transposed-letter targets of Experiment 1 were presented as masked primes in Experiment 2, followed by the corresponding real word target (*drakness-DARKNESS* vs. *dcekness-DARKNESS*/*darnkess-DARKNESS* vs. *darvbess-DARKNESS*). The same pseudo-suffixed and non-suffixed items of Experiment 1 were also used. A full list of stimuli is provided in Appendix 2. A set of 120 nonword targets was constructed with a nonword stem (*uvon*) generated by the ARC nonword database (http://www.maccs.mq.edu.au/~nwdb/) onto which we added the morphemic and non-morphemic endings used in the real word conditions (*acid-ic* vs. *uvon-ic*). Word and nonword targets were matched on length. For each item type, we obtained a matched set of nonword targets: truly suffixed (*uvon-ic* vs. *acid-ic*), pseudo-suffixed (*ilon-ity* vs. *amen-ity*), and non-suffixed (*cebb-ast* vs. *ball-ast*). Nonword targets were preceded by a either a TL or a SL prime (*uovnic-UVONIC* vs. *uebnic-UVONIC*/*uvoinc-UVONIC* vs. *uvoerc-UVONIC*).

Procedure

Stimuli were presented as letter strings in Courier New 12pt, in the centre of a computer screen. The experimental software used was the DMDX display system (Forster & Forster, 2003). Each trial consisted of a 600 ms forward mask of hash keys presented in the centre of the screen, followed by a 50 ms prime in lowercase and the uppercase target. The number of has keys was matched with the number of letters of the prime. Following Rastle et al.'s (2004) design, target words were presented individually and were not embedded into flanking symbols (e.g. %%TARGET%%). The presentation of the target remained until the participant responded or until a maximum response delay of three seconds was reached. The participants used a response box with two different keys with one for the positive and one for the negative lexical decision response. Participants were instructed to reply as quickly and accurately as possible. The trials were presented in randomised order including a break in the middle. Twenty practice trials were presented at the beginning of the session.

Results

Response latencies faster than 300 ms (32 data points) and longer than 1500 ms (167 data points) were discarded from the data set (1.6% of the correct responses). This method was chosen as response times longer than 1500 ms were typically identified as individual outliers rather than related to the overall speed of the subject. Other trimming procedures were tried, and produced a similar pattern of results. Mean response latencies and accuracy scores averaged across subjects are presented in Table 3.

Table 3. *Table 3 presents mean lexical decision times and error rates for word targets averaged across subjects in Experiment 2. Standard deviations are shown in parentheses.*

Condition		Reaction times	Error Rates	Example
		Truly suffixed		
TL-within		629 (123)	14.3 (13.7)	d**ra**kness-DARKNESS
SL-within		641 (128)	14.6 (13.4)	d**ce**kness- DARKNESS
	TL-effect	12	0.3	
TL-across		624 (110)	15.1 (13.5)	dar**nk**ess- DARKNESS
SL-across		644 (116)	15.6 (13.0)	dar**vb**ess- DARKNESS
	TL-effect	20	0.5	
		Pseudo-suffixed		
TL-within		596 (105)	9.8 (10.7)	g**ol**ssary-GLOSSARY
SL-within		607 (102)	10.4 (11.4)	g**it**ssary-GLOSSARY
	TL-effect	11	0.6	
TL-across		590 (107)	8.5 (10.5)	glos**as**ry-GLOSSARY
SL-across		598 (95)	10.7 (11.7)	glos**et**ry-GLOSSARY
	TL-effect	8	2.2	
		Non-suffixed		
TL-within		622 (101)	15.0 (15.7)	c**sa**hew-CASHEW
SL-within		637 (110)	17.2 (16.5)	c**ri**hew-CASHEW
	TL-effect	15	2.2	
TL-across		619 (114)	16.0 (14.2)	cas**eh**w-CASHEW
SL-across		637 (111)	18.9 (16.3)	cas**if**w-CASHEW
	TL-effect	18	2.9	

Response latencies were transformed logarithmically and the main analyses were performed using linear mixed effect model methodology as in Experiment 1. For each Item Type (Truly Suffixed, Pseudo-suffixed, Non-suffixed) and each Position (Within, Across) a separate generalised linear mixed-effects model was created with two fixed effects factors (Trial Number and Prime Type: Transposed-letter, Substituted-letter) and two random-effects factors (random intercepts for Subjects and Items). Significance was accessed with p-value sampling *pvals.fnc*, as implemented in the language R package (Baayen, 2008).

These analyses revealed a significant transposed-letter priming effect in the truly suffixed TL-within condition (*drakness-DARKNESS*; 12 ms, $t = 2.02$, $p < .043$), and in the truly suffixed TL-across condition (*darnkess-DARKNESS*; 20 ms, $t = 3.15$, $p < .002$). Similarly, in the Pseudo-suffixed conditions, there was a robust transposed-letter priming effect in the TL-within condition (*golssary-GLOSSARY*; 11 ms; $t = 2.14$, $p < .032$) and in the TL-across condition (*glosasry-GLOSSARY*; 8 ms; $t = 2.57$, $p < .010$). Also in the Non-suffixed control conditions, a transposed-letter priming effect was obtained for both within-boundary (*csahew-CASHEW*, 15 ms, $t = 3.36$, $p < .001$), and across-boundary transpositions (*casehw-CASHEW*, 18 ms, $t = 3.8$, $p < .001$).

Three additional analyses for each Item Type were performed to further explore the transposed-letter effect sizes within as compared to across the boundary using a generalised linear mixed-effects model with four fixed effects factors (Trial Number, TL-Status: Transposed-letter, Substituted-letter; Position: Within, Across and interaction between TL-Status and Position) and two random-effects factors (random intercepts for Subjects and Items). There was a significant main transposed-letter effect in the truly suffixed condition, $t = 3.36$, $p < .001$, in the pseudo-suffixed condition, $t = 2.53$, $p = .012$, and in the non-suffixed condition, $t = 3.69$, $p < .001$. None of the interactions were significant.

In addition, for the purpose of directly comparing effect sizes between item types, we performed three separate pair-wise comparisons using generalised linear mixed-effects models with eight fixed effects factors (Trial Number, TL-Status: Transposed-letter, Substituted-letter; Position: Within, Across; Item Type: Truly Suffixed, Pseudo-suffixed/Truly Suffixed, Non-suffixed/Pseudo-suffixed, Non-suffixed; interaction of TL-Status and Position; interaction of TL-Status and Item Type; interaction of Position and Item Type; and interaction of TL-Status; Position and Item Type) and two random-effects factors (random intercepts for Subjects and Items). There was a significant main transposed-letter effect across truly and pseudo-suffixed trials, $t = 2.49$, $p = .013$, across truly and non-suffixed trials, $t = 3.58$, $p < .001$, and across pseudo and non-suffixed trials, $t = 3.66$, $p < .001$. Overall, pseudo-suffixed trials were responded to faster than truly suffixed trials, $t = 3.55$, $p < .001$, and non-suffixed trials, $t = 2.95$, $p = .003$. No interactions were significant.

In order to examine the pattern of results across all items, we collapsed across Item Type and a generalised linear mixed-effects model was used with two fixed effects factors (Trial Number and Prime Type: Transposed-letter, Substituted-letter) and two random-effects factors (random intercepts for Subjects and Items). The main effect of Position was not significant. The analysis revealed a significant transposed-letter priming effect across all items, $t = 7.0$, $p < .001$. This effect did not vary across individual item types. The nonword data showed no significant effects.

In the error data, a set of generalised linear mixed-effects models was fitted following the design of analysis used in the response latency data. The analysis showed a marginally significant main transposed-letter priming effect in the pseudo-suffixed condition, $t = 1.93$, $p = .054$, and a significant main TL-priming effect in the non-suffixed condition, $t = 2.14$, $p = .032$. None of the interactions were significant. The pair-wise comparisons between item types revealed that participants made significantly less errors classifying pseudo-suffixed words than non-suffixed words, $t = 2.47$, $p = .013$. No other effects were significant. The overall generalised linear mixed-effects analysis revealed a significant transposed-letter priming effect across all items, $t = 7.0$, $p < .001$. This effect did not vary across individual item types. No other effects were significant.

Discussion

The goal of Experiment 2 was to use masked TL-priming to test if morphologically complex words can be directly accessed as wholes at initial processing stages, as predicted by the supralexical account and the hybrid model, or whether word recognition is based on a structural segmentation mechanism which blindly decomposes any complex letter string into morphemic subunits at initial word processing stages, as predicted by the obligatory decomposition account and the form-then-meaning account, and whether or not early morphological parsing is affected by the semantic characteristics of the prime.

The results showed that the transposed-letter priming effect was present for truly suffixed and pseudo-suffixed within-boundary transpositions (*d**ra**kness/g**ol**ssary*) and for non-suffixed words (*c**sa**hew/cas**eh**w*). We found significant TL-priming for both truly suffixed and pseudo-suffixed across-boundary transpositions. In line with Experiment 1, this finding provides evidence against the hypothesis that the transposed-letter priming effect diminishes when letter transpositions cross the morpheme boundary in truly affixed or pseudo-affixed words. The present data are thus consistent with the theory that morphologically complex words can be directly accessed as whole words at initial word processing stages. Moreover, no difference was found between the size of priming obtained in the truly and pseudo-suffixed condition, which suggests that the semantic interpretability of the prime does not interact with early morphological decomposition processes.

In addition, both response latency data and error data confirmed that there was no overall difference between the size of TL-priming obtained in the within morpheme boundary conditions (*d**ra**kness*, *g**ol**ssary*, *c**sa**hew*, etc.) as compared to the across morpheme boundary conditions (*dar**nk**ess*, *glos**as**ry*, *cas**eh**w*, etc.). This effect did not vary for individual item types. We can therefore rule out the presence of a left-to-right checking strategy as observed in Experiment 1.

The transposed-letter priming effects obtained in Experiment 2 can only be explained in terms of a whole-word access route, since priming of the target *darkness* by the prime *dar**nk**ess* can only be achieved if imprecise encoding of the letters in *dar**nk**ess* directly activates the full form representation of *darkness* at very early stages in visual word recognition. This is in line with the predictions made by the supralexical account (Giraudo & Grainger, 2001) and the hybrid model (Diependaele et al., 2009). If *darkness* was not represented in this form, there would be no activation of *darkness* through *dar**nk**ess*; instead the recognition system would rely on the parsing of the stimulus into morpho-orthographic sub-structures which would then be used as access units to the whole-word. Given that the morpheme boundary in *dar**nk**ess* has been disrupted, the parsing of the letter string would fail and herewith the activation of the representation of *darkness*. Similarly, if the process of recognizing a pseudo-suffixed word was always based on the prior decomposition into morphological form units, the disruption of the pseudo-boundary in *glos**as**ry* would critically impair the activation of the representation of *glossary*. The present results are thus inconsistent with the obligatory decomposition account (Taft, 1994, 2003) and the form-then-meaning account (Crepaldi et al., 2010). Both accounts propose that the recognition of truly and pseudo affixed words can only be achieved through prior decomposition into its morpho-orthographic subunits, predicting the absence of TL-priming for across morpheme boundary transpositions.

Finally, there was no difference between the effect sizes of truly suffixed, pseudo-suffixed and non-suffixed TL-priming which indicates that semantic information did not affect early morphological processing and suggests that the obtained priming effects were triggered by early orthographic whole-word activations. This finding was unexpected given that our results support the supralexical account and hybrid model in terms of whole-word access, but suggest that any semantic activation related to these whole-word representations must occur downstream from this initial orthographic activation and are thus not reflected in the priming (we return to this point in the General Discussion).

In summary, our data show that morphologically complex words can be accessed as full forms. Of course, it should not be concluded from this that morphologically complex words are *not* decomposed. As outlined earlier, there is a large body of evidence in favor of morphological decomposition (Longtin & Meunier, 2005; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Rastle et al., 2004). Rather our results are in line with models of visual word recognition which emphasize the simultaneous activation of whole-word and morphemic representations. For instance, the hybrid model considers that word recognition can be achieved in parallel through a whole-word route as well as a decompositional pathway to maximize the reader's chances of successful word processing through simultaneous use of all mechanisms available to them.

If such parallel processing does occur, it should be possible to find evidence for morphological decomposition using the same materials that previously revealed evidence for whole-word processing. To test this prediction, we used our materials in a design first adopted by Rastle and colleagues (2004). They carried out a masked priming lexical decision experiment to compare priming effects on stem-target recognition for truly suffixed (*darkness-DARK*) and pseudo-suffixed prime-target pairs (*glossary-GLOSS*) relative to a non-suffixed control (*cashew-CASH*). Given that this design tests to what degree stem-target recognition is facilitated by the prior presentation of a morphologically related prime, it is particularly sensitive to decomposition mechanisms involved in morphologically complex word recognition. Their results showed priming in the truly suffixed and in the pseudo-suffixed conditions, but not in the non-suffixed condition, suggesting that morphological decomposition takes place independently of semantic and syntactic constraints. Their data provide evidence for a morphological decomposition mechanism operating over true morphological structure and morphological pseudo-structure at early prelexical processing stages. Following Rastle's design, the targets of Experiment 2 were presented as primes in Experiment 3 followed by their stem targets.

Experiment 3

Method

Participants

Sixty-two undergraduate and graduate students participated in this study for course credit or monetary reimbursement. All participants were native English speakers.

Materials

The 120 targets of Experiment 2 were presented in lowercase as masked primes in Experiment 3, followed by the stem as a lexical decision target (*darkness-DARK*, *glossary-GLOSS*, and *cashew-CASH*). For each prime, a semantically and orthographically unrelated control prime was selected. All control primes were truly or pseudo-suffixed, however prime and control never shared the same suffix. Related and unrelated primes were matched on length, logarithmic frequency and orthographic N. In line with Rastle et al. (2004), an additional set of 40 unrelated word pairs were included to further reduce the prime-target relatedness proportion. A full list of stimuli is provided in

Appendix 3. The same 120 nonword stems of Experiment 2 were presented as uppercase targets, preceded by a truly or pseudo-suffixed real word prime (*talked-UVON*). Nonword targets and primes were orthographically unrelated. The word and nonword targets were matched on length, so were the primes.

Procedure

The procedure was adapted from Experiment 2. However, as this was a replication of Rastle et al. (2004), we slightly modified the prime duration (40 ms) to match the settings of that study.

Results

No outliers were discarded as error rates were below 30%. Moreover, neither standard-deviation trimming (discarding reaction times above or below 3.0 *SD*s each participants mean reading time), nor absolute-value trimming (using 300 ms as a low cut-off and 1500 ms as a high cut-off) changed the size and the direction of the main effects and interactions. Mean response latencies and accuracy scores were analysed for each subject and are presented in Table 4.

Table 4. *Table 4 presents mean lexical decision times and error rates for word targets averaged across subjects in Experiment 3. Standard deviations are shown in parentheses.*

Condition	Reaction times	Error Rates	Example
Truly suffixed			
related	555 (94)	7.5 (6.3)	darkness-DARK
unrelated	584 (107)	10.9 (8.3)	perilous-DARK
priming effect	29	3.4	
Pseudo-suffixed			
related	566 (101)	10.8 (8.3)	glossary-GLOSS
unrelated	586 (86)	13.1 (8.6)	flattery-GLOSS
priming effect	20	2.3	
Non-suffixed			
related	590 (83)	13.8 (10.7)	cashew-CASH
unrelated	599 (101)	14.0 (9.1)	seeing-CASH
priming effect	9	0.2	

As in Experiment 1 and 2, the response latencies were transformed logarithmically and the main analyses were performed using linear mixed effect model modelling (e.g. Baayen, 2008;

Baayen et al., 2008). Significance was accessed with p-value sampling *pvals.fnc*, as implemented in the language R package (Baayen, 2008). Only those fixed effects and random effects are presented below that significantly improved the model's fit in a stepwise model selection procedure.

For each item type, a separate generalised linear mixed-effects model was fitted using two fixed effects factors (Trial Number and Prime Type[1]: Related, Unrelated) and two random-effects factors (random intercepts for Subjects and Items). The results of the Truly Suffixed data revealed that targets preceded by truly suffixed primes (*darkness-DARK*) were responded to significantly faster (by 29 ms) than their unrelated controls (*perilous-DARK*), t = 6.71, p < .001. Similarly, words preceded by Pseudo-suffixed items (*glossary-GLOSS*) were classified significantly faster (by 20 ms) than the unrelated controls (*flattery-GLOSS*), t = 5.33, p < .001. In the Non-suffixed condition, only a non-significant 9 ms difference was found between the related (*cashew-CASH*) and the unrelated trials (*seeing-CASH*).

An additional analysis across all items was performed, based on a generalised linear mixed-effects model with four fixed effects factors (Trial Number, Prime Type: Related, Unrelated; Item Type: Truly Suffixed, Pseudo-suffixed, Non-suffixed, and interaction between Prime Type and Item Type) and two random-effects factors (random intercepts for Subjects and Items). The model revealed that pseudo-suffixed trials were responded to faster than non-suffixed trials, t = 2.02, p <.044, and truly suffixed trials were responded to faster than non-suffixed trials, t = 2.32, p <.020, whereas there was no difference between truly suffixed and pseudo-suffixed trials, t = 0.47, p <.639. Priming was significantly greater in the pseudo-suffixed than priming in the non-suffixed condition, t = 2.41, p <.016, and priming in the truly suffixed condition was significantly greater than priming in the non-suffixed condition, t = 3.04, p <.002, but there was no significant difference between the priming in the truly suffixed and pseudo-suffixed conditions, t = 0.61, p <.541.

Following the design of analysis used in the response latency data, the accuracy data revealed significant priming in the truly suffixed condition (3.4%), t = 3.43, p < .001, and in the pseudo-suffixed condition (2.3%), t = 2.18, p < .030. Priming in the non-suffixed condition was not significant (0.2%). Moreover, the analysis across all items types revealed a significant overall priming effect, t = 3.17, p <.002. The other effects were not significant. There was no significant effect in the nonword data.

[1] Except in the Non-suffixed condition, the factor Prime Type was not included, as it did not significantly improve the model's fit.

Discussion

The first point to note about these results is that the two morphological conditions unambiguously produced masked priming effects, which did not differ as a function of whether the prime comprised a true morphological structure (*darkness-DARK*) or simply a morphological pseudo structure (*glossary-GLOSS*), as evidenced by both response latency and accuracy data. These results indicate that prelexical morphological decomposition does occur with the prime stimuli we used.

Our findings replicate the findings of Rastle and colleagues (2004) and are consistent with the view that morphologically complex words are decomposed at early automatic stages in visual word recognition, even when there is no semantic relationship between the morphologically complex prime and the stem target. Our findings add evidence to a growing body of studies showing that there is at least one mechanism operating at initial word recognition stages which blindly parses any letter string with an apparent polymorphemic structure (McCormick et al., 2009; Meunier & Longtin, 2007). Moreover, the data are incompatible with post-lexical accounts of written polymorphemic word processing (Giraudo & Grainger, 2001, 2003; Marslen-Wilson et al., 1994; Plaut & Gonnerman, 2000). If morphological decomposition was a semantically driven process, no priming would be expected for pseudo-suffixed primes, and this is inconsistent with the observed pattern.

The lack of difference in the magnitude of priming obtained for truly and pseudo-affixed primes (see also Rastle et al., 2004; Longtin & Meunier, 2005) has typically been taken as evidence for an early automatic morphological decomposition mechanism which operates over morphological structure before the word's meaning is available (Rastle & Davis, 2008). This account however has been challenged by findings demonstrating that morphological decomposition may not exclusively rely on a morpho-orthographic parsing mechanism (Diependaele et al., 2009; Feldman et al., 2009; Meunier & Longtin, 2007). For instance, increased amounts of priming have been found for truly-affixed relative to pseudo-affixed primes using unmasked (Feldman & Soltano, 1999; Marslen-Wilson et al., 1994) and masked priming (Diependaele et al., 2005), suggesting that influences from the representation of the whole-word can occur at very early stages in word recognition. Another study by Feldman et al. (2009) indicated that a numerical advantage for truly affixed over pseudo affixed primes in masked priming has almost always been observed. A meta-analysis of the 16 masked priming studies reported by Rastle and Davis (2008) revealed a significant advantage for truly suffixed as compared to pseudo-suffixed items.

These results seem to indicate that early stages of word processing rely on a more complex interplay of parallel processing routes. Besides a morpho-orthographic segmentation mechanism which blindly occurs for any letter string with the mere appearance of morphological complexity (Longtin & Meunier, 2005; Rastle et al., 2004), a second mechanism appears to operate simultaneously providing feedback from a whole-word level (Diependaele et al., 2009). On this account, while the present study demonstrates that there *is* a morpho-orthographic segmentation mechanism occurring at early prelexical stages in visual word recognition, the lack of difference in the magnitude of the masked priming effects between truly and pseudo-suffixed primes does not indicate that this mechanism is exclusive.

General Discussion

The present experiments bring together the findings from two domains of morphological research which have in the past often been regarded as two competing accounts: whole-word access and morphological decomposition. Our findings provide evidence for both.

Recently it has been vigorously debated as to whether decomposition is purely based on the analysis of orthography (Rastle & Davis, 2008) or whether whole-word processing may occur at early processing stages (Diependaele et al., 2009; Feldman et al., 2009). Related to this, theories have differed about whether there is a direct pathway to the representation of a complex full form (Diependaele et al., 2009; Giraudo & Grainger, 2003; Figure 1, Panel B and D) or whether words are always recognized on basis of their stem morphemes (Rastle & Davis, 2008; Taft, 2003; Figure 1, Panel A and C).

The goal of our research was to address this question and test whether (i) complex word recognition can be achieved through a direct access route to the representation of the whole-word or if complex words are obligatorily decomposed into morphemic subunits which are then used as access units to the lexicon and (ii) if semantic factors influence early morphological processing. Experiment 1 compared truly suffixed, pseudo-suffixed and non-suffixed TL-nonword targets in the context of unprimed lexical decision and revealed significant transposed-letter effects for within-boundary and across-boundary transpositions across all item types. In addition, a positional left-to-right checking effect was found such that nonwords with letter transpositions at early positions in the letter string (*d**ra**kness, g**ol**ssary, c**sa**hew*) were rejected faster than nonwords with letter transpositions at a late position (*dar**nk**ess, glos**as**ry, cas**eh**w*). Experiment 2 replicated the findings of Experiment 1 in the context of masked priming, showing significant transposed-letter priming for both within-boundary and across-boundary transpositions. As opposed to Experiment 1 however, the size of TL-priming for within (*d**ra**kness-DARKNESS, g**ol**ssary-GLOSSARY, c**sa**hew-CASHEW*) and across-boundary transpositions (*dar**nk**ess-DARKNESS, glos**as**ry-GLOSSARY, cas**eh**w-CASHEW*) did not differ. Moreover, equal amounts of priming were obtained in the truly suffixed, pseudo-suffixed and non-suffixed condition.

Taken together, the findings of Experiment 1 and 2 are inconsistent with the hypothesis that the transposed-letter priming effect decreases for across-boundary transpositions and are thus inconsistent with the theory that morphologically complex words are always recognized on basis of their morphemic subunits (Rastle & Davis, 2008; Taft, 2003). The present data instead suggest that the recognition of a morphologically complex word can be achieved through a direct access route to the representation of the whole-word (Diependaele et al., 2009; Giraudo & Grainger, 2001).

In this regard, the present work is in line with Rueckl and Rimzhim's findings (2010), showing that transposed-letter priming effects do not decrease for across-boundary transpositions in English suffixed words. Inconsistent with our own findings, however, are the data reported by Duñabeitia et al. (2007) who found significant TL-priming in the within-boundary condition, but not in the across-boundary conditions. One critical difference between Duñabeitia et al.'s, Rueckl and Rimzhim's and our own experiments was the context in which affixes were presented. As Rueckl and Rimzhim's study, we explicitly used the same affixes in both word and nonword trials (*amen-ity* vs. *ilon-ity*), whereas the nonword fillers used by Duñabeitia et al. (2007) were primarily non-affixed (with a few exceptions). Moreover, while in the present experiments affixes occured as part of true morphological structures (*dark-ness*) and morphological pseudo-structures (*gloss-ary*), the affixes in Duñabeitia et al.'s and Rueckl and Rimzhim's study always occurred as part of semantically transparent stem-affix combinations.

Given that in Duñabeitia et al's participants encountered affixes only if the stimulus was a truly affixed word, and never when it was a nonword or a pseudo-affixed word, it is possible that participants may have relied on affixes as processing cues to a larger extent than was the case in our experiments, leading to a bias of the recognition system. Since the majority of the non-affixed primes were followed by a nonword target, the absence of an affix in the prime would have been a strong indicator for a negative lexical decision response. That is, participants could have attempted to parse any input letter string into stem and affix, which would have only succeeded in words in which the affix as a parsing unit was maintained (*d**ra**kness*). However, for any letter string in which the affix was disrupted (*dar**nk**ess*) the detection of the affix would fail, causing the vanishing of the transposed-letter priming effect. In the present studies, however, the detection and stripping of an affix itself would not have been sufficient to make an accurate lexical decision response, which may explain why the activation of the whole-word (*darkness*) was not only successful when the affix was kept intact (*d**ra**kness*), but also when it was disrupted (*dar**nk**ess*). Similar to our studies, Rueckl and Rimzhim presented affixes not only as part of real words, but also in the context of nonwords, which rules out the possibility that participants used affixes as lexical decision cues.

The discrepancy between Rueckl and Rimzhim's and our own as compared to Duñabeitia et al.'s results may also be associated with language-specific differences across studies. It cannot be ruled out that reading systems of different languages with varying morphological structures may differ (Frost, 2009; Frost, Kugler, Deutsch, & Forster, 2005). Being an agglutinative language, Basque differs from Spanish and English in its highly productive morphological nature, that is, most Basque words are formed by at least two joined morphemes. Moreover, while both English and Spanish are non-agglutinative languages, the Spanish morphology is characterised by a significantly richer morphological diversity and productivity. Compared to English for example, Spanish affixation is used to express diminutives (e.g. *casa*/*casita* [house/small house] or *gato*/*gatito* [cat/kitten]), augmentatives (e.g. *rico*/*riquísimo* [good/delicious]), pejoratives (e.g. *casa*/*casucha* [house/house that is falling apart]) or gender related information (suffix *a* expresses female gender, suffix *o* expresses male gender). Due to the relatively rich nature of Basque and Spanish morphology, the morphological parsing system may therefore constitute a more central component of the reading system than is the case in English. Further research is needed to systematically compare differences across languages.

In addition, Rueckl and Rimzhim (2010) report that transposed-letter priming effects within and across the boundary were robust across three different prime presentation durations (48, 66, and 100 ms). In light of these findings, it seems unlikely that the conflicting findings of Duñabeitia et al. and the present studies can be attributed to different presentation durations (66 ms and 50 ms respectively).

Critically, the data of Experiment 1 and 2 further demonstrate that there was no difference between the effect sizes of truly suffixed, pseudo-suffixed and non-suffixed TL-similarity. The present findings thus suggest that semantics do not influence initial orthographic whole-word activations and indicate that a word's orthographic form must be processed before its meaning can become available. This finding was unexpected given that the two models supported by our findings (the supralexical account and hybrid model) both postulate an early onset of morpho-semantic processing. It thus appears that, although the supralexical account and the hybrid model predict that morpho-semantic effects should occur earlier than in the other two models (the obligatory decomposition account and the form-then-meaning account), influences from semantics may still not arise early enough to become evident in masked morphological priming. In fact, when participants were given more time to process the input stimulus, as in the context of unprimed lexical decision in Experiment 1, there was a tendency towards transposed-letter effects being larger in the truly suffixed conditions than in the pseudo-suffixed conditions, suggesting that semantically transparent derivations (*darkness*) are activated more strongly than semantically opaque letter strings (*glossary*).

Most critically, the findings in Experiment 1 and 2 demonstrate that very early stages of morphological processing are purely orthographic and that orthographic whole-word representations are already available at these early stages. This is inconsistent with the idea that semantic similarity influences initial stages of morphological processing (Feldman et al., 2009) and hence supports theories proposing that initial word recognition stages are always purely orthographic independently of influences from semantic word properties (e.g. Crepaldi et al., 2010; Diependaele et al., 2009; Rastle et al., 2004; Rastle & Davis, 2008; Taft, 2003). That is, any semantic activation related to these whole-word representations must occur downstream from these initial orthographic activation stages and are thus not reflected in the priming. Due to the lack of evidence for morpho-semantic processing in the present set of experiments, it cannot be concluded at what exact stage in the reading system semantics are first taken into account. Further research is needed in order to investigate when exactly semantics begin to influence morphological processing.

Finally, the results of Experiment 3 are in line with previous evidence from masked morphological priming obtained in various languages (for reviews, see Frost, Grainger, & Carreiras, 2008; Frost, Grainger, & Rastle, 2005). The priming effects found for truly suffixed (*darkness-DARK*) and pseudo-suffixed (*glossary-GLOSS*) primes support the proposal of a prelexical segmentation mechanism which decomposes any letter string with an apparent morphological structure (see Rastle et al., 2004). The lack of priming of the non-suffixed condition (*cashew-CASH*) suggests that the obtained priming effects were not due to orthographic overlap.

Taken together, the evidence presented in the present work provides clear constraints on theories of how readers process morphologically complex letter strings. While Experiments 1 and 2 support models which argue that morphologically complex words can be directly retrieved as full forms, Experiment 3 is consistent with the theory that morphologically complex words are decomposed at early prelexical stages in visual word recognition. These findings are inconsistent with the supralexical decomposition account (Giraudo & Grainger, 2001) which suggests that the initial stages of word processing are *uniquely* based on the retrieval of whole-word forms which may be post-lexically decomposed at a later stage. They are also inconsistent with the obligatory decomposition account (Taft, 1994, 2003) and the form-then-meaning account (Crepaldi et al., 2010) proposing that the recognition of a complex word is *always* guided by a morpheme-based access on the recognition of its morphemic subunits.

A model of morphologically complex word recognition which can account for the evidence presented in our paper has been proposed: the hybrid model (Figure 1, Panel D; Diependaele et al., 2009). On this account, morphologically complex input strings are mapped in parallel onto both morpho-orthographic representations, applicable to every letter string comprising a morphological surface structure, and orthographic whole-word representations. The authors propose the existence of an orthographic form level at which words with the mere appearance of morphological complexity are decomposed into morphemic subunits. On this level, truly affixed words like *darkness* and pseudo affixed words like *glossary* would be decomposed into *dark* and *ness* or *gloss* and *ary*. The morphemic form representations would then send further activation to the corresponding lexical representations *dark* and *gloss*. The hybrid model further proposes a second parallel processing route such that every mono- and polymorphemic real word is directly mapped from the orthographic form level onto a corresponding whole-word representation in the lexicon. In this view, morphologically complex whole-word recognition can be achieved directly and independently from the morphological parsing route.

The hybrid model seems to provide an account for the pattern of results across Experiments 1, 2 and 3. First, the hybrid model offers an explanation for the results obtained in Experiment 1 and 2. On this account, the disruption of structural information such as letter position manipulations at morpheme boundary (*dar**nk**ess*) would indeed have inhibitory consequences for the morpho-orthographic parsing route. Critically however, the processing of the letter string would succeed through the direct activation route, such that *dar**nk**ess* would be directly mapped onto the closest matching whole-word representation in the lexicon, *darkness*. In the case of intact morpheme boundary information, as in within morpheme-boundary transpositions like *d**ra**kness*, the processing of the stimulus would be mediated either on the basis of morphemic parsing into sub-structures or via the whole-word activation route. That is, significant priming would be equally expected for both within- and across-boundary transpositions, which is in line with the data presented in Experiments 1 and 2. Second, the hybrid model gives an account for the results described in Experiment 3. Given that at the level of orthographic form any letter string with the mere appearance of morphological complexity is segmented into affix and remaining letter strings, truly and pseudo-affixed words would be decomposed into stem and affix. Thus, in the context of masked priming, the prelexical activation of *dark* and *gloss* through *darkness* and *glossary* would both produce priming, which is consistent with the data presented in Experiment 3.

In summary, Experiments 1 and 2 demonstrate that morphologically complex words like *darkness* can be accessed as whole-words, from which it follows that they do not *need* to be morphologically decomposed, Experiment 3 however indicates that they are. Experiment 3 illustrates that morphological decomposition occurs for complex words, from which it follows that they do not *need* to be processed as whole units, but Experiment 1 and 2 show that they are. We conclude that the orthographic lexicon is a storage-system containing monomorphemic and polymorphemic word forms which can be accessed via a direct whole-word route and through a prelexical morpho-orthographic decomposition route.

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Appendix 1

Appendix 1 presents the stimuli used in Experiment 1. Basewords are listed first, which are followed by the four corresponding TL-targets in the following order: TL-within target, SL-within target, TL-across target and SL-across target.

Truly suffixed condition: *acidic, aicdic, aefdic, aciidc, acielc; angelic, agnelic, anuplic, angeilc, angeorc; armoury, amroury, afsoury, armouyr, armouwt; burglary, bugrlary, bursvary, burglayr, burglamn; bushy, bsuhy, brihy, busyh, busmk; earthy, erathy, ealnhy, eartyh, eartwm; abortive, aobrtive, aegrtive, aboritve, aborulve; adoptive, aodptive, aerptive, adopitve, adopunve; bulbous, blubous, bnibous, bulobus, buligus; cheapen, cehapen, cifapen, cheaepn, cheaixn; darkest, drakest, dsikest, darekst, darifst; demonic, dmeonic, dkaonic, demoinc, demoerc; dullest, dlulest, dsolest, dulelst, dulinst; edition, eidtion, eantion, ediiton, ediason; faulty, faluty, fanity, faulyt, faulkr; firmest, frimest, flumest, firemst, firakst; forgery, frogrey, flugrey, forgrey, forgsay; freely, ferely, fasely, freley, freroy; gawky, gwaky, gfoky, gawyk, gawcm; hostess, hsotess, hlitess, hosetss, hosirss; humanity, hmuanity, hueknity, humainty, humaorty; idyllic, iydllic, iwnllic, idylilc, idylotc; itemize, ietmize, iasmize, iteimze, iteawze; longest, lnogest, lrugest, lonegst, lonipst; magician, mgaician, maebcian, magiican, magiedan; musician, msuician, muencian, musiican, musiewan; naivety, niavety, nagoety, naivtey, naivroy; optician, otpician, opescian, optiican, optiufan; perilous, preilous, paeslous, periolus, periadus; pricey, pircey, padcey, pricye, pricwo; scratchy, srcatchy, scramlhy, scratcyh, scratcfk; sensory, snesory, sedvory, sensoyr, sensokn; sharpen, sahrpen, siwrpen, sharepn, sharivn; symbolic, sybmolic, sygwolic, symboilc, symboetc; syrupy, sryupy, snhupy, syruyp, syrumb; tighten, tgihten, tjahten, tighetn, tigharn; trainee, tarinee, tulinee, traiene, traiude; validate, vaildate, vaocdate, valiadte, valiurte; wakeful, wkaeful, wmieful, wakfeul, wakhiul; workable, wrokable, wlikable, worakble, worimble.*

Pseudo-suffixed condition: *amenity, aemnity, aufnity, ameinty, ameusty; basket, bsaket, bliket, basekt, basumt; blanket, balnket, bisnket, blanekt, blanoft; bucket, bcuket, bfoket, bucekt, bucift; buffet, bfufet, bmofet, bufeft, bufiht; cellar, clelar, cnilar, celalr, celusr; charity, cahrity, cefrity, chairty, chausty; classic, calssic, codssic, clasisc, clasodc; dental, dnetal, drutal, denatl, denosl; dollar, dlolar, dnilar, dolalr, dolenr; glossary, golssary, gitssary, glosasry, glosetry; helmet, hlemet, hramet, helemt, helokt; infantry, ifnantry, ihlantry, infanrty, infanlsy; junket, jnuket, jtoket, junekt, junawt; market, mraket, mloket, marekt, marict; marshal, mrashal, mleshal, marsahl, marseyl; naughty, nauhgty, naucpty, naughyt, naughws; passive, psasive, pnosive, pasisve, pasetve; phoney, pohney, piwney, phonye, phonfa; picket, pciket, pwaket, picekt, picast; pillar, plilar, pridar, pilalr, pilenr;*

planet, palnet, pidnet, plaent, plaust; portal, protal, psatal, poratl, porisl; racket, rcaket, rwoket, racekt, racimt; rational, raitonal, raedonal, ratioanl, ratioedl; rustic, rsutic, rdetic, rusitc, rusedc; sandal, snadal, sludal, sanadl, sanitl; several, sveeral, spueral, sevearl, seveinl; signet, sginet, svonet, sigent, sigalt; solely, sloely, sriely, solley, soltoy; storey, stroey, stlaey, storye, storwa; tactic, tcatic, thotic, tacitc, tacusc; tangent, tnagent, tdigent, tanegnt, tanopnt; tangle, tnagle, tligle, tanlge, tandpe; tartar, tratar, tsitar, taratr, taresr; thicket, thciket, thwaket, thicekt, thicoft; tourist, tuorist, taerist, touirst, touanst; wallet, wlalet, wnulet, walelt, walint; warden, wraden, wsiden, waredn, waroln; wicket, wciket, wfoket, wicekt, wicaht.

Non-suffixed condition: *appendix, appnedix, appsadix, appenidx, appenurx; ballast, blalast, bsilast, balalst, balurst; basilica, baislica, baoylica, basiilca, basietca; brothel, borthel, bidthel, brotehl, brokuml; bungalow, bnugalow, bregalow, bunaglow, buniplow; button, btuton, bsaton, butotn, butisn; cashew, csahew, crihew, casehw, casifw; champagne, cahmpagne, cifmpagne, chamapgne, chamibgne; charisma, cahrisma, coyrisma, chairsma, chautsma; chateau, cahteau, cikteau, chaetau, chailau; colonel, coolnel, coirnel, coloenl, coloisl; dialog, dailog, duelog, diaolg, diaeng; extract, exrtact, exndact, extrcat, extrmut; fleece, felece, fasece, flecee, flefae; fondue, fnodue, ftadue, fonude, fonire; freeze, fereze, fateze, frezee, frexue; galaxy, glaaxy, gruaxy, galxay, galpey; galleon, glaleon, gsileon, galelon, galiron; glade, galde, ginde, glaed, glaus; inferno, ifnerno, iklerno, infenro, infedso; masseur, msaseur, mriseur, masesur, masidur; mastiff, msatiff, mrutiff, masitff, maserff; messiah, msesiah, mtusiah, mesisah, mesotah; mildew, mlidew, mradew, miledw, milanw; mustang, msutang, mdotang, musatng, musosng; pollute, plolute, pselute, polulte, polaste;*
pulpit, plupit, prepit, pulipt, pulabt; rabbit, rbabit, rvebit, rabbti, rabbde; scarab, sacrab, sifrab, scaarb, scaunb; scrape, scarpe, scotpe, scraep, scraiz; shovel, sohvel, sikvel, shovle, shovru; solemn, sloemn, sniemn, solmen, solyan; spinach, sipnach, sevnach, spianch, spiolch; starve, satrve, sinrve, stavre, stagre; studio, sutdio, seldio, stuido, stuero; surgeon, srugeon, srugeon, surgoen, surgaun; tactile, tcatile, tmotile, tacitle, tacusle; textile, txetile, tpatile, texitle, texodle; turnip, trunip, tsenip, turinp, turesp; vestige, vsetige, vdutige, vesitge, vesulge.

Appendix 2

Appendix 2 presents the stimuli used in Experiment 2. Target words are listed first in uppercase, immediately followed by its corresponding TL-within prime, SL-within prime, TL-across prime and then followed by the SL-across prime. All four primes are presented in lowercase.

Truly suffixed condition: *ACIDIC, aicdic, aefdic, aciidc, acielc; ANGELIC, agnelic, anuplic, angeilc, angeorc; ARMOURY, amroury, afsoury, armouyr, armouwt; BURGLARY, bugrlary, bursvary, burglayr, burglamn; BUSHY, bsuhy, brihy, busyh, busmk; EARTHY, erathy, ealnhy, eartyh, eartwm; ABORTIVE, aobrtive, aegrtive, aboritve, aborulve; ADOPTIVE, aodptive, aerptive, adopitve, adopunve; BULBOUS, blubous, bnibous, bulobus, buligus; CHEAPEN, cehapen, cifapen, cheaepn, cheaixn; DARKEST, drakest, dsikest, darekst, darifst; DEMONIC, dmeonic, dkaonic, demoinc, demoerc; DULLEST, dlulest, dsolest, dulelst, dulinst; EDITION, eidtion, eantion, ediiton, ediason; FAULTY, faluty, fanity, faulyt, faulkr; FIRMEST, frimest, flumest, firemst, firakst; FORGERY, frogrey, flugrey, forgrey, forgsay; FREELY, ferely, fasely, freley, freroy; GAWKY, gwaky, gfoky, gawyk, gawcm; HOSTESS, hsotess, hlitess, hosetss, hosirss; HUMANITY, hmuanity, hueknity, humainty, humaorty; IDYLLIC, iydllic, iwnllic, idylilc, idylotc; ITEMIZE, ietmize, iasmize, iteimze, iteawze; LONGEST, lnogest, lrugest, lonegst, lonipst; MAGICIAN, mgaician, maebcian, magiican, magiedan; MUSICIAN, msuician, muencian, musiican, musiewan; NAIVETY, niavety, nagoety, naivtey, naivroy; OPTICIAN, otpician, opescian, optiican, optiufan; PERILOUS, preilous, paeslous, periolus, periadus; PRICEY, pircey, padcey, pricye, pricwo; SCRATCHY, srcatchy, scramlhy, scratcyh, scratcfk; SENSORY, snesory, sedvory, sensoyr, sensokn; SHARPEN, sahrpen, siwrpen, sharepn, sharivn; SYMBOLIC, sybmolic, sygwolic, symboilc, symboetc; SYRUPY, sryupy, snhupy, syruyp, syrumb; TIGHTEN, tgihten, tjahten, tighetn, tigharn; TRAINEE, tarinee, tulinee, traiene, traiude; VALIDATE, vaildate, vaocdate, valiadte, valiurte; WAKEFUL, wkaeful, wmieful, wakfeul, wakhiul; WORKABLE, wrokable, wlikable, worakble, worimble*.

Pseudo-suffixed condition: *AMENITY, aemnity, aufnity, ameinty, ameusty; BASKET, bsaket, bliket, basekt, basumt; BLANKET, balnket, bisnket, blanekt, blanoft; BUCKET, bcuket, bfoket, bucekt, bucift; BUFFET, bfufet, bmofet, bufeft, bufiht; CELLAR, clelar, cnilar, celalr, celusr; CHARITY, cahrity, cefrity, chairty, chausty; CLASSIC, calssic, codssic, clasisc, clasodc; DENTAL, dnetal, drutal, denatl, denosl; DOLLAR, dlolar, dnilar, dolalr, dolenr; GLOSSARY, golssary, gitssary, glosasry, glosetry; HELMET, hlemet, hramet, helemt, helokt; INFANTRY, ifnantry, ihlantry, infanrty, infanlsy; JUNKET, jnuket, jtoket, junekt, junawt; MARKET, mraket, mloket, marekt, marict; MARSHAL, mrashal, mleshal, marsahl, marseyl; NAUGHTY, nauhgty, naucpty, naughyt, naughws; PASSIVE, psasive, pnosive, pasisve, pasetve; PHONEY, pohney, piwney, phonye, phonfa; PICKET, pciket, pwaket, picekt, picast;*

PILLAR, plilar, pridar, pilalr, pilenr; PLANET, palnet, pidnet, plaent, plaust; PORTAL, protal, psatal, poratl, porisl; RACKET, rcaket, rwoket, racekt, racimt; RATIONAL, raitonal, raedonal, ratioanl, ratioedl; RUSTIC, rsutic, rdetic, rusitc, rusedc; SANDAL, snadal, sludal, sanadl, sanitl; SEVERAL, sveeral, spueral, sevearl, seveinl; SIGNET, sginet, svonet, sigent, sigalt; SOLELY, sloely, sriely, solley, soltoy; STOREY, stroey, stlaey, storye, storwa; TACTIC, tcatic, thotic, tacitc, tacusc; TANGENT, tnagent, tdigent, tanegnt, tanopnt; TANGLE, tnagle, tligle, tanlge, tandpe; TARTAR, tratar, tsitar, taratr, taresr; THICKET, thciket, thwaket, thicekt, thicoft; TOURIST, tuorist, taerist, touirst, touanst; WALLET, wlalet, wnulet, walelt, walint; WARDEN, wraden, wsiden, waredn, waroln; WICKET, wciket, wfoket, wicekt, wicaht.

Non-suffixed condition: *APPENDIX, appnedix, appsadix, appenidx, appenurx; BALLAST, blalast, bsilast, balalst, balurst; BASILICA, baislica, baoylica, basiilca, basietca; BROTHEL, borthel, bidthel, brotehl, brokuml; BUNGALOW, bnugalow, bregalow, bunaglow, buniplow; BUTTON, btuton, bsaton, butotn, butisn; CASHEW, csahew, crihew, casehw, casifw; CHAMPAGNE, cahmpagne, cifmpagne, chamapgne, chamibgne; CHARISMA, cahrisma, coyrisma, chairsma, chautsma; CHATEAU, cahteau, cikteau, chaetau, chailau; COLONEL, coolnel, coirnel, coloenl, coloisl; DIALOG, dailog, duelog, diaolg, diaeng; EXTRACT, exrtact, exndact, extrcat, extrmut; FLEECE, felece, fasece, flecee, flefae; FONDUE, fnodue, ftadue, fonude, fonire; FREEZE, fereze, fateze, frezee, frexue; GALAXY, glaaxy, gruaxy, galxay, galpey; GALLEON, glaleon, gsileon, galelon, galiron; GLADE, galde, ginde, glaed, glaus; INFERNO, ifnerno, iklerno, infenro, infedso; MASSEUR, msaseur, mriseur, masesur, masidur; MASTIFF, msatiff, mrutiff, masitff, maserff; MESSIAH, msesiah, mtusiah, mesisah, mesotah; MILDEW, mlidew, mradew, miledw, milanw; MUSTANG, msutang, mdotang, musatng, musosng; POLLUTE, plolute, pselute, polulte, polaste; PULPIT, plupit, prepit, pulipt, pulabt; RABBIT, rbabit, rvebit, rabbti, rabbde; SCARAB, sacrab, sifrab, scaarb, scaunb; SCRAPE, scarpe, scotpe, scraep, scraiz; SHOVEL, sohvel, sikvel, shovle, shovru; SOLEMN, sloemn, sniemn, solmen, solyan; SPINACH, sipnach, sevnach, spianch, spiolch; STARVE, satrve, sinrve, stavre, stagre; STUDIO, sutdio, seldio, stuido, stuero; SURGEON, srugeon, srugeon, surgoen, surgaun; TACTILE, tcatile, tmotile, tacitle, tacusle; TEXTILE, txetile, tpatile, texitle, texodle; TURNIP, trunip, tsenip, turinp, turesp; VESTIGE, vsetige, vdutige, vesitge, vesulge*.

Appendix 3

Appendix 3 presents the stimuli used in Experiment 3. Target words are listed first in uppercase, immediately followed by its corresponding related prime and then followed by the unrelated prime, both in lowercase.

Truly suffixed condition: *ACID, acidic, fluffy; ANGEL, angelic, teacher; ARMOUR, armoury, toughen; BURGLAR, burglary, laudable; BUSH, bushy, petal; EARTH, earthy, griped; ABORT, abortive, jealousy; ADOPT, adoptive, stealthy; BULB, bulbous, throaty; CHEAP, cheapen, tougher; DARK, darkest, zealous; DEMON, demonic, tracery; DULL, dullest, eatable; EDIT, edition, wealthy; FAULT, faulty, beaten; FIRM, firmest, wrestle; FORGE, forgery, galling; FREE, freely, darker; GAWK, gawky, acted; HOST, hostess, summery; HUMAN, humanity, suitable; IDYLL, idyllic, ailment; ITEM, itemize, velvety; LONG, longest, payable; MAGIC, magician, slippery; MUSIC, musician, fixation; NAIVE, naivety, charter; OPTIC, optician, weakling; PERIL, perilous, actually; PRICE, pricey, fairer; SCRATCH, scratchy, periodic; SENSOR, sensory, taxable; SHARP, sharpen, weakest; SYMBOL, symbolic, accepted; SYRUP, syrupy, beaker; TIGHT, tighten, cryptic; TRAIN, trainee, rolling; VALID, validate, weaponry; WAKE, wakeful, blacken; WORK, workable, attacker.*

Pseudo-suffixed condition: *AMEN, amenity, loyalty; BASK, basket, poetry; BLANK, blanket, nursery; BUCK, bucket, speedy; BUFF, buffet, partly; CELL, cellar, mainly; CHAR, charity, modesty; CLASS, classic, quietly; DENT, dental, brandy; DOLL, dollar, sentry; GLOSS, glossary, flattery; HELM, helmet, shifty; INFAN, infantry, friendly; JUNK, junket, soured; MARK, market, sourly; MARSH, marshal, meanest; NAUGHT, naughty, organic; PASS, passive, nearest; PHONE, phoney, casket; PICK, picket, worthy; PILL, pillar, avowed; PLAN, planet, stingy; PORT, portal, calmer; RACK, racket, brewer; RATION, rational, greenery; RUST, rustic, boiler; SAND, sandal, rotate; SEVER, several, ruinous; SIGN, signet, barbed; SOLE, solely, burner; STORE, storey, darken; TACT, tactic, curler; TANG, tangent, sourest; TANG, tangle, deafen; TART, tartar, dealer; THICK, thicket, sparkle; TOUR, tourist, spidery; WALL, wallet, dearer; WARD, warden, firmly; WICK, wicket, frizzy.*

Non-suffixed condition: *APPEND, appendix, gorgeous; BALL, ballast, prowess; BASIL, basilica, cheapest; BROTH, brothel, cubicle; BUNG, bungalow, casualty; BUTT, button, oldest; CASH, cashew, seeing; CHAMP, champagne, effective; CHAR, charisma, bearable; CHAT, chateau, fleeing; COLON, colonel, dearest; DIAL, dialog, cheeky; EXTRA, extract, cruelty; FLEE, fleece, arming; FOND, fondue, acting; FREE, freeze, ageing; GALA, galaxy, asking; GALL, galleon, crumble; GLAD, glade, messy; INFER, inferno, fairest; MASS, masseur, crunchy; MAST, mastiff, frailty; MESS, messiah, flighty; MILD,* *mildew, fixate; MUST, mustang, flowery; POLL, pollute, fishery; PULP, pulpit, joyous; RABBI, rabbit, stocky; SCAR, scarab, drawer; SCRAP, scrape, crafty; SHOVE, shovel, brassy; SOLE, solemn, pantry; SPIN, spinach, freeing; STAR, starve, fairly; STUD, studio, girdle; SURGE, surgeon, soloist; TACT, tactile, gravely; TEXT, textile, sweater; TURN, turnip, glassy; VEST, vestige, greatly.*

Early morphological decomposition during visual word recognition: Evidence from masked transposed-letter priming.

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Abstract

The present studies were designed to explore the theory of early morpho-orthographic segmentation (Rastle, Davis, & New, 2004), which postulates that written words with a true morphologically complex structure ('cleaner') and those with a morphological pseudo-structure ('corner') are decomposed into affix and stem morphemes. We used masked complex transposed-letter nonword primes in a lexical decision task. Experiment 1 replicated the well-known masked transposed-letter (TL) priming effect using monomorphemic nonword primes ('wran-WARN'). Experiment 2 used the same nonword TL-stems as Experiment 1, but combined with real suffixes ('ish' as in 'wranish-WARN'). Priming was compared with that from non-suffixed primes in which the real suffixes were replaced with non-morphemic endings ('-el' as in 'wranel-WARN'). Significant priming was found in the suffixed but not in the non-suffixed condition, suggesting that affix-stripping occurs at pre-lexical stages in visual word recognition and operates over early letter-position encoding mechanisms.

Keywords: visual word recognition, masked priming, morphological processing, morphological decomposition.

Early morphological decomposition during visual word recognition: Evidence from masked transposed-letter priming.

How do readers gain access to the orthographic lexical entries of morphologically complex printed words? Three different classes of theory have been proposed here. There are full-listing theories which consider the lexicon as a store of full forms in which lexical representations of morphologically complex words are accessed only by whole-word representations (e.g. Butterworth, 1983; Manelis & Tharp, 1977). There are purely-morphological-access theories claiming that lexical representations of morphologically complex words are accessed only by the representations of the word's constituent morphemes (e.g. Longtin & Meunier, 2005; Rastle et al., 2004; Taft & Forster, 1975). And there are dual-access theories which postulate that lexical representations of morphologically complex words can be accessed on the basis of either a whole word representation or by the representations of the word's constituent morphemes (Baayen, Dijkstra, & Schreuder, 1997; Diependaele, Sandra, & Grainger, 2009).

Support for theories positing morphological decomposition has come from unmasked priming, which has demonstrated the influence of morphological structure on word reading (e.g. Diependaele et al., 2009; Marslen-Wilson, Tyler, Waksler, & Older, 1994), but also from masked priming, where recognition of stem targets has been found to be facilitated by prior presentation of morphologically related primes (e.g. Longtin, Segui, & Hallé, 2003; Rastle, Davis, Marslen-Wilson, & Tyler, 2000).

However, debate continues as to the nature of this decomposition process. Some theorists favour a morpho-semantic account, in which decomposition occurs only where the meaning of a complex word can be derived from the meaning of its stem morpheme and the syntax of its suffix (e.g. Giraudo & Grainger, 2000; Giraudo & Grainger, 2001). Others argue for a purely structural morpho-orthographic decomposition process. For instance, Rastle et al. (2004) used masked priming to compare priming effects for morphologically related prime-target pairs for which the meaning could either be derived from the meaning of its morphemic subunits ('cleaner-CLEAN') or not ('corner-CORN'). Priming for both types of words was found, suggesting that morphological decomposition takes place independently of semantic and syntactic constraints. These data indicate that morphological decomposition is based on a pre-lexical affix-stripping process first proposed by Taft & Forster (1975) which operates in a way such that every word bearing a true morphological structure ('cleaner') or a morphological pseudo-structure ('corner') is decomposed.

However, questions about affix-stripping remain that cannot be addressed by the data of Rastle et al. (2004). Given that the primes in the Rastle et al. study were always words, it cannot be ruled out that affix-stripping is only triggered when a complex letter-string *is itself a word*. If affix-stripping depends on purely structural information, morphological priming should occur independently of whether the prime is a real word or a nonword. To distinguish between these two hypotheses, Longtin & Meunier (2005) used a masked priming procedure in which the primes were always nonwords. Their lexical decision study in French compared priming effects on stems of semantically interpretable ('rapidifier-RAPIDE') and non-interpretable nonword primes ('sportation-SPORT') and found similar-sized effects relative to a non-morphological control, suggesting that morphological decomposition occurs for all morphologically-structured items, even if they are not words. Recently, McCormick et al. (2008; 2009) extended these findings to English demonstrating that complex words with common orthographic alterations in the stem morpheme (such as a missing 'e' as in 'adorable-ADORE'; McCormick et al., 2008) and morphologically complex nonword primes with orthographic alterations in the stem morpheme ('adorage-ADORE'; McCormick et al., 2009) produced significant priming to the stem target.

Our study aimed to extend these findings to the domain of letter-transpositions for the purpose of further controlling lexicality and semantic interpretability and locating more precisely the stage of processing at which affix-stripping occurs. To further minimize the prime's resemblance to a real word and its semantic interpretability, our nonword primes consisted of stems that were *letter-transpositions* (TL) of the target words ('wranish', comprising TL-stem 'wran' and suffix 'ish'). It is well-established that masked TL-nonwords such as the stems used in our study ('wran') prime their corresponding real word targets ('warn') relative to a substituted-letter (SL) control ('whun'; Andrews, 1996; Forster, Davis, Schoknecht, & Carter, 1987; Perea & Lupker, 2003), an effect typically attributed to the uncertainty in position coding in early stages of visual word recognition (e.g. Perea & Lupker, 2004).

No previous study has explored stem-target recognition in the context of masked complex TL-nonword priming. If the nonword prime 'wranish' facilitates lexical decision to the target word 'WARN', three conclusions can be drawn. Firstly, consistent with the findings of Longtin and Meunier (2005), affix-stripping is triggered automatically and independently of whether or not a word has been activated in the orthographic lexicon, since "wranish" is not a word (and is not a TL-transposition of any word). Secondly, morphologically-structured letter-strings are decomposed despite little or no semantic relatedness between their constituents. And thirdly, this affix-stripping process occurs very early in word recognition, operating at the same stage as that at which letter-position is coded.

We report two experiments. Experiment 1 was designed to replicate the basic transposed-letter priming effect using our materials. Monomorphemic TL-nonwords were presented as primes, followed by the baseword of the stem morpheme ('wran-WARN') and participants performed lexical decisions on the target words. Based on previous literature, we expected significant priming from

TL-nonwords relative to orthographic control primes. Then, in our key Experiment 2, we used the same items as in Experiment 1 as primes but in a morphologically complex form: stem targets were preceded by suffixed TL-nonword primes ('wranish-WARN'). Priming was compared with that found in a non-morphological condition in which primes were created by adding a non-morphological ending ('el') to the TL-nonword stem ('wranel-WARN'). If morphological decomposition is purely based on the early and automatic recognition of an affix, priming should occur in the morphological and not in the non-morphological condition.

Experiment 1

Method

Participants

Sixty undergraduate and graduate students, all native English speakers, participated for course credit or monetary reimbursement.

Materials

Thirty-six monomorphemic 4-5 letter long target words were selected from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993). For each target we created a TL-nonword prime by transposing the letters in the second and third position ('wran-WARN'). A SL-control condition was created, as typically used in TL-experiments (e.g. Perea & Lupker, 2003), by substituting the transposed letters ('ra' in 'wran') with two new letter identities ('hu') in every TL-nonword prime ('whun-WARN'). Seventy-two nonword targets were extracted from the ARC nonword database (Rastle, Harrington, & Coltheart, 2002). All nonwords were orthographically legal and pronounceable and matched with the word targets on length, position-specific bigram frequency, position-specific trigram frequency and Coltheart's N. Each nonword target ('smoob') was used to create a TL- ('somob') and a SL-prime ('sepob'). The experiment used two testing blocks so that each two related primes (i.e. the TL-prime and the SL-prime) would never appear together. A full list of stimuli may be downloaded from http://pbr.psychonomic-journals.org/content/supplemental.

Procedure

Stimuli were presented in the centre of a CRT computer screen using the DMDX display system (Forster & Forster, 2003) in randomised order. Each trial consisted of a 500ms forward mask of hash-marks, then a 40ms prime in lowercase, then the uppercase target stimulus which appeared in the same position as the hash-marks. The target remained on the screen until the participant responded or until three seconds had elapsed. Participants were instructed to respond as quickly and accurately as possible.

Results and Discussion

Word and nonword trials were analysed separately. All word trials with incorrect responses (9.8% of the total) were trimmed. No outliers were discarded as neither Standard Deviation Trimming (discarding reaction times above or below 2.0 *SD*s or 3.0 *SD*s each participants mean reading time), nor high & low cut-off trimming (using 300ms as a low cut-off and 1500ms or 1300ms as a high cut-off) changed the size or direction of any main effects or interactions. Mean reaction times (RT) and error rates averaged over subjects are presented in Table 1.

Table 1. *Experiment 1: Mean reaction times (in ms) and percentage of errors for real word targets averaged across subjects. Standard deviations are shown in parentheses.*

Condition	Reaction times	Error Rates	Example
TL	525 (75)	9.2 (7.6)	wran-WARN
SL	538 (72)	10.4 (8.7)	whun-WARN
TL-effect	13	1.2	

Reaction times were transformed logarithmically and the main analyses were performed using linear mixed-effect model methodology (Baayen, 2008). To reduce the variance in the models, we included the predictor Trial Number as a measure of how far participants had progressed into the experiment, allowing control for longitudinal task effects such as fatigue or habituation. Furthermore, since every participant saw items in a different random order, trial order may have had different effects on individual subjects. Therefore, to adjust by-subject random slopes for Trial Number, we included a correlation parameter specified in the random-effect structure of each subject (Baayen, 2008, pp.251-252). A generalised linear mixed-effects model as implemented in the lme4 package (from http://cran.r-project.org/web/packages/) in the statistical software R (version 2.10.1, RDevelopmentCoreTeam, 2008) was used, with two fixed-effects factors (Trial Number and Prime Type [TL/SL]) and two random-effects factors (random intercepts for Subjects and Items). Factors were considered separately in a step-wise selection procedure, in the following order: random intercepts for Subjects, random intercepts for Items, Trial Number, by-subject random slopes for Trial Number, Prime Type, Morphological Complexity (Experiment 2 only) and the Interaction of Prime Type and Morphological Complexity (Experiment 2 only), and were only included in the mixed-effects model if formal comparisons between models showed a significant improvement of the model's fit when the factor was included. Significance was assessed with p-value sampling *pvals.fnc*, as implemented in the language R package (Baayen, 2008). The model revealed that words preceded by TL-nonwords were classified significantly faster (13ms) than words preceded by SL-nonwords, t=-3.1, p=.002, showing that TL-priming occurs with our particular set of monomorphemic items. The effect of Trial Number was significant, t=-3.27, p<.001. The significance of factor Prime Type did not change when factor Trial Number was omitted. The mixed-effects analysis of error and nonword data revealed no significant results.

Thus, Experiment 1 successfully replicated the previously reported masked TL-priming effect using our own materials.

Experiment 2

Method

Participants

One hundred and twenty undergraduate and graduate students, all native English speakers, participated in this study for course credit or monetary reimbursement.

Materials

The same targets as in Experiment 1 were used in the suffixed and in the non-suffixed conditions. Primes in the suffixed condition were created by adding a real suffix to the stem ('wran-ish'/'whun-ish'), whereas primes in the non-suffixed condition were created by adding a non-morphological ending ('wran-el'/'whun-el'). To avoid effects ascribed to the baseword of the whole prime, we selected stem and affix combinations in a way that ensured the entire prime was not a TL-transposition of any real word (as in 'wraned'/'warned'). Both TL-conditions were matched with their corresponding set of control items on length, consonant-vowel structure, position-specific bigram frequency and position-specific trigram frequency. A full list of stimuli may be downloaded from http://pbr.psychonomic-journals.org/content/supplemental.

The same nonword targets of Experiment 1 and the same morphemic and non-morphemic endings used to create nonword primes in the word trials were used to create the nonword trials ('somobful'/'sepobful'). Four different lists were created using a Latin Square Design and tested with different subject groups.

Procedure

The same procedure as in Experiment 1 was used.

Results and Discussion

Word and nonword trials were analysed separately. All word trials with incorrect responses (8.1% of the total) were trimmed. As in Experiment 1, no outliers were discarded, because the analysis of the trimmed data did not change the size or the directions of the main effects and interactions. Mean RT and error rates were analysed following the procedures of Experiment 1 and are presented in Table 2.

Table 2. *Experiment 2: Mean reaction times (in ms) and percentage of errors for real word targets averaged across subjects. Standard deviations are shown in parentheses.*

Condition	Reaction times	Error Rates	Example
	Suffixed		
TL	555 (91)	7.9 (11.5)	wranish-WARN
SL	571 (103)	8.4 (11.7)	whunish-WARN
TL-effect	16	0.5	
	Non-suffixed		
TL	571 (97)	7.1 (11)	wranel-WARN
SL	567 (85)	9.1 (11.9)	whunel-WARN
TL-effect	-4	2.0	

Similarly to Experiment 1, a mixed-effects model analysis of logRT data was carried out, with four fixed-effects factors (Trial Number, Morphological Complexity [suffixed/non-suffixed], Prime Type [TL/SL] and the interaction between Morphological Complexity and Prime Type) and two random-effects factors (random intercepts for Subjects and Items). As in Experiment 1, Trial Number was included as a predictor. The model revealed a significant main linear effect of Prime Type, t=-3.1, p=.003. The main effect of Morphological Complexity was not significant, t=0.3, p=.757. The interaction of Prime Type and Morphological Complexity indicated that TL-facilitation only occurred in the suffixed but not in the non-suffixed condition, t=2.4, p=.017.

In addition, the suffixed and non-suffixed data sets were fitted to two separate linear models with two fixed-effects factors (Trial Number and Prime Type [TL/SL]) and two random-effects factors (random intercepts for Subjects and Items). The suffixed data showed a significant linear effect of Prime Type, t=-3.0, p=.003 (less than the Bonferroni-corrected value); words preceded by suffixed TL-nonwords were responded to 16ms faster than words preceded by suffixed SL-nonwords. The effect of Trial Number was not significant, t=-1.1, p=.252. In the non-suffixed data, the effect of Trial

Number was non-significant, t=-2.2, p=.031 (greater than the Bonferroni-corrected value). The effect of Prime Type was not significant, t=0.3, p=.764.

The significance of the obtained results did not change when factor Trial Number was omitted. None of the error data and nonword data effects was significant.

The degree of orthographic overlap between a subset of the TL-primes with an existing suffixed letter-string ('wranish' overlaps with 'warning') did not significantly correlate with the TL-priming effect (r=.073, t=0.6, p=.540). Moreover, to explore whether there was a relationship between TL-priming and position-specific bigram frequency, length of final letter sequences ('el', 'ish', etc.) or position-specific boundary bigram frequency of the bigrams at morpheme boundaries ('ni' in 'wranish'), we entered these as correlation variables. The difference between the suffixed and non-suffixed TL-priming effect did not correlate significantly with position-specific bigram frequency (r=.047, t=0.4, p=.693) or length (r=.080, t=0.7, p=.504) of the final letter sequences nor with position-specific boundary bigram frequency (r=.003, t=0.03, p=.978).

The finding that the masked presentation of a suffixed TL-nonword facilitates the recognition of the baseword of the stem morpheme ('wranish-WARN') whereas non-suffixed TL-nonword primes do not ('wranel-WARN') shows that priming cannot be attributed to simple orthographic overlap and provides evidence in support of a theory of visual word recognition in which there is pre-lexical morphological decomposition operating over early letter-position encoding mechanisms. Most critically, the data extend Longtin & Meunier's (2005) and McCormick et al's (2009) results to the domain of letter-transposition priming effects, providing evidence for affix-stripping in the absence of semantic relatedness.

General Discussion

The transposed-letter priming effect obtained in Experiment 2 can only be explained in terms of morphological decomposition, since priming of the target 'WARN' by the prime 'wranish' can only be achieved if there is a mechanism that isolates the stem of the prime at very early stages in visual word recognition. The present data are thus inconsistent with full listing accounts (e.g. Butterworth, 1983; Manelis & Tharp, 1977) that reject the decomposition hypothesis. Our results are also incompatible with purely post-lexical accounts of morphological decomposition which assume that access to morphemic subunits does not occur until after whole word representations have been accessed (Giraudo & Grainger, 2001; Giraudo & Grainger, 2003). As those models postulate that only existing morphologically complex words are decomposed, nonwords such as those in our current experiments would be rejected by the word recognition system and therefore not decomposed. However, although our findings provide evidence against post-lexical decomposition accounts, they do not rule out models allowing two parallel access routes (Baayen et al., 1997; Caramazza, Laudanna, & Romani, 1988; Diependaele et al., 2009), a decompositional route and a full form route, or models proposing morphological segmentation at the level of lemmas (e.g. Crepaldi, Rastle, Coltheart, & Nickels, 2010).

Our data are consistent with previous findings that decomposition of morphologically-structured items occurs in the presence of an affix, independently of whether the affix is a sub-constituent of a true morphological structure (‘cleaner-CLEAN’), a morphological pseudo-structure (e.g. 'corn-er', Rastle et al., 2004), or a morphologically-structured nonword (‘quickify-QUICK’, ‘sportation-SPORT’, Longtin & Meunier (2005); ‘adorage-ADORE’, McCormick et al., 2009). Our data extend these findings to the transposed-letter priming domain showing TL-priming in the context of morphologically-structured TL-nonword primes (‘wranish-WARN’). All TL-nonword primes used in the morphological condition of Experiment 2 were meaningless: the combination of the TL-nonword ‘wran’ or its corresponding baseword ‘warn’ with the suffix (‘ish’) resulted in a meaningless letter-string (‘wranish’ or ‘warnish’). This lack of meaning minimizes the possibility that priming effects were driven by semantic relationships between prime and target. Morphological decomposition instead appears to be triggered purely by the presence of affixes, allowing fast and automatic access to internal structure of words.

Affix-representations can be thought of as a strongly-memorized list of highly productive morphological subunits which can be accessed at very early stages of visual word processing. A letter-chunk that successfully matches an affix-representation (‘ish’ in ‘wranish’) is rapidly identified while the word recognition system continues searching for deeper lexical structures throughout the rest of the letter-string. After affix-stripping, the remaining letter-string ‘wran’ activates (with positional uncertainty) the representation of ‘warn’, producing priming. Non-morphemic endings like ‘el’ as in ‘wranel’, however, are not memorized in the same manner and not used as triggers to detect morpho-orthographic sub-structures; therefore affix-stripping fails and no priming occurs.

One alternative possibility is that the obtained effects were driven by lower-level orthographic stimulus features, such as frequency or length of the final letter sequences or frequency of morpheme boundary bigrams. A difference between suffixed and non-suffixed items on these factors could potentially influence priming by affecting the ease with which stem morphemes can be activated in the lexicon. However, there was no relationship between TL-priming and position-specific bigram frequency, length of morphemic or non-morphemic endings, or position-specific boundary bigram frequency, which would appear to rule out such an account.

Given that the wranish-WARN effect cannot be attributed to low-level features of the prime or semantic overlap between prime and target, we conclude that the observed priming constitutes a morphological effect. Our studies suggest that affix-stripping is triggered by a mechanism operating at very early orthographic processing stages while letter-position coding is not yet fully resolved, showing that morphemic structure and letter-position are coded at the same stage, prior to lexical access. These findings thus have implications for theories of letter-position coding (Davis, 2010; Whitney, 2001) suggesting that the encoding of letter-identity and letter-position may embody knowledge of morphemic structure. That is, orthographic analysis does not uniquely rely on the coding of lower-level visual processing features, as higher-level linguistic factors appear to be taken into account at the same time. However, many questions still remain to be answered. For example, we note that other findings in relation to morpho-orthographic decomposition, such as the reported absence of priming when TL manipulations occur across morpheme boundaries (‘clea**en**r’) as opposed to within them (‘c**el**aner’; Christianson, Johnson, & Rayner, 2005; Duñabeitia, Perea & Carreiras, 2007), would seem to rely on affix-stripping drawing on precise letter-position information and occurring after letter-position has been resolved. Further research is needed to reveal the precise relationship between letter-position coding and affix-stripping.

Our account above would further predict that primes like ‘wransih’ should also produce priming to the target ‘WARN’, relative to an orthographic control. However such effects may not be as strong, since the decoding of transposed-letter affixes might conflict with the lesser degrees of positional uncertainty at the word’s ends (Perea & Lupker, 2007). Future investigations could explore to what extent positional imprecision can be tolerated and if this can also be extended to affixal units.

In summary, the present experiments suggest that affix-representations are matched with input letter-strings independently of the lexical and semantic context in which they occur, allowing fast decomposition of affixed words or nonwords, even in the presence of letter-transpositions. This thus confirms previous evidence for affix-stripping operating over early orthographic encoding mechanisms and allows us to locate morphological decomposition temporally at very early, semantically ‘blind’ pre-lexical stages of word recognition.

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Early morphological decomposition of suffixed words: Masked priming evidence with transposed-letter nonword primes

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Abstract

Many studies have previously reported that the recognition of a stem target (e.g. *teach*) is facilitated by the prior masked presentation of a prime consisting of a derived form of it (e.g. *teacher*). We conducted two lexical decision experiments to investigate masked morphological priming in Spanish. Experiment 1 showed that equal magnitudes of masked stem-target priming are obtained for both morphologically complex word primes (e.g. *doloroso-DOLOR* [*painful-PAIN*]) and morphologically complex nonword primes that included letter transpositions within the stem (e.g. *dlooroso-DOLOR*). Experiment 2 used morphologically complex nonword primes comprising lexically illegal combinations of stems and suffixes (e.g. *total + ito* [*a little total*]). Priming was obtained for morphologically related nonword primes (e.g. *totalito-TOTAL*), but not for nonword primes that included letter transpositions within the pseudo-stem (e.g. *ttoalito-TOTAL*). Our data suggest that morpho-orthographic parsing mechanisms benefit from semantic constraints at early stages in the reading system, which we discuss in the context of current morphological processing accounts.

Keywords: visual word recognition, masked priming, transposed-letters, letter position coding

Early morphological decomposition of suffixed words: Masked priming evidence with transposed-letter nonword primes

Many decades of research have been directed towards understanding how and when readers gain access to morphological information in visual word recognition (Bybee, 1995; Colé, Beauvillain, & Segui, 1989; Taft & Forster, 1975). Full-listing theories propose that morphologically complex words are stored and retrieved as whole entities in the lexicon (e.g. Butterworth, 1983; Manelis & Tharp, 1977). Recently however, research has begun to more extensively explore the concept of morphological decomposition. Post-lexical decomposition accounts propose that morphologically complex words are always initially mapped onto whole-word representations and only decomposed after access to the lexicon has been achieved (e.g. Giraudo & Grainger, 2000; Giraudo & Grainger, 2001). Pre-lexical accounts of morphological decomposition suggest that morphologically structured words are automatically decomposed into their morpho-orthographic subunits which then in turn activate the lexical representation of the whole word (e.g. Duñabeitia, Perea, & Carreiras, 2007; (Grainger, Colé, & Segui, 1991; Longtin & Meunier, 2005; Longtin, Segui, & Hallé, 2003); Rastle, Davis, Marslen-Wilson, & Tyler, 2000; Rastle, Davis, & New, 2004; Taft, 2003, 2004). Other researchers favour a dual-pathway account, proposing a combination of pre- and post-lexical decomposition strategies, such that a morphologically complex input letter string can be either processed pre-lexically (via the decompositional pathway) or post-lexically (via the whole-word route; e.g., Diependaele, Sandra, & Grainger, 2009; see also Baayen, Dijkstra, & Schreuder, 1997, for a related account).

More recently, it has been debated as to when exactly semantic influences in automatic morphological processing can be found. In this respect, theories of morphological decomposition split into two different camps. One hypothesis proposes that early morphological decomposition is purely based on the analysis of orthographic form (e.g. McCormick, Rastle & Davis, 2008, 2009; Rastle & Davis, 2008). This hypothesis argues that morphological decomposition is initially semantically ‘blind’, as it operates purely on the basis of *morpho-orthographic* encoding, and that *morpho-semantic* information then gradually comes in as time increases. The second hypothesis considers that semantic influences on morphological parsing can already be observed at initial stages of word recognition (e.g. Diependaele et al., 2009; Feldman, O’Connor, Moscoso del Prado Martin, 2009). Results favouring this view have been obtained in experiments reporting processing asymmetries between truly polymorphemic words (such as the derived word *teacher*), and pseudo-complex monomorphemic words that have an internal structure that resembles that of polymorphemic words (such as *corner*, which could be incorrectly decomposed in *corn+er*; see

Feldman et al., 2009, for review). It is thus considered that morpho-orthographic and morpho-semantic processing co-occur at initial morphological processing stages.

The masked priming paradigm has been typically used to explore automatic stages of the processing of derivationally-affixed words (Longtin et al., 2003; Rastle, Davis, Marslen-Wilson, & Tyler, 2000). In a prototypical masked priming experiment, a forward mask is presented, followed by a briefly presented stimulus (the prime), which in turn is immediately replaced by another stimulus (the target). Participants are not aware of the existence of the masked prime, but its influence can still be measured on target recognition. The processing of the briefly presented prime (typically shown for 40-70 ms) is posited to show early, automatic processes (Forster & Davis, 1984; Forster, Davis, Schoknecht, & Carter, 1987). In this line, many masked priming studies have shown that the recognition of a target (e.g. *corn*) is facilitated by the prior presentation of a morpho-orthographically related prime (e.g. *corner*), suggesting that there is a mechanism that decomposes morphologically complex letter strings at early pre-lexical stages in visual word recognition (e.g. Longtin & Meunier, 2005).

Our present studies aimed at further investigating early morphological decomposition and affix stripping mechanisms in visual word recognition in masked priming to explore whether priming still occurs for morphologically complex primes including a letter transposition within their stems (Experiment 1) and exploring the influences of semantics on early morphological transposed-letter priming effects by altering the lexical status of the primes (Experiment 2). As explained below, this manipulation represents a critical test for accounts based on early and automatic morphological decomposition, due to the orthographic nature of the transposed-letter similarity effect (TL effect, hereafter, see also Christianson, Johnson, & Rayner, 2005; Duñabeitia, Perea, & Carreiras, 2007; Rueckl & Rimzhim, in press).

Evidence from masked transposed-letter priming studies shows that a nonword prime with two transposed letters at internal positions such as *wlak* facilitates the recognition of the target *walk* relative to an orthographic control like *whuk* (e.g. Andrews, 1996; Forster et al., 1987; Perea & Lupker, 2003; Peressotti & Grainger, 1999; Schoonbaert & Grainger, 2004). This masked TL-similarity effect can be accounted for by models of orthographic encoding that assume imprecise initial coding of letter positions at early stages of word processing (Gómez, Ratcliff, & Perea, 2008; Grainger & van Heuven, 2003; Whitney, 2001). As a consequence of the imprecise position encoding of the letters within a string, when a TL-nonword like *wlak* is presented the orthographic representation of the word *walk* is activated, and consequently the lexical representation of the word *walk* is the one receiving the highest activation, since this is the closest pattern matching the misspelled input (see Duñabeitia, Perea, & Carreiras, 2009). Hence, the TL-effect is assumed to reflect positionally imprecise whole-word processing (Gómez et al., 2008).

In a recent lexical decision study in English, Rueckl and Rimzhim (2010) investigated the effects of TL-manipulations in morphological masked priming to test the time course of morphological processing in visual word recognition. Critically, as compared to previous studies (e.g. Christianson et al., 2005; Duñabeitia et al., 2007) which have always used morphologically complex targets, Rueckl and Rimzhim (2010, Experiment 1-3) were the first to investigate the effects of TL-manipulated morphologically complex word primes on stem-target recognition. Primes were created by either transposing the two last letters of the stem (*teahcer-TEACH*) or by transposing the last letter of the stem and the first of the suffix (*teacehr-TEACH*). An additional condition was introduced in which targets were preceded by a morphologically related prime (*teacher-TEACH*). TL-primes and morphologically related primes were compared to a substituted-letter control, in which the two transposed letters (*teahcer*) were substituted with two new letter identities (*teakser*).

These experiments revealed that the recognition of the target (*teach*) was facilitated by the prior masked presentation of morphologically related TL-primes, independently of whether it comprised a TL-manipulation within the stem or across the morpheme boundary (*teahcer-TEACH vs. teacehr-TEACH*). These results conflict with previous findings (Christianson et al., 2005; Duñabeitia et al., 2007) suggesting that the position of the transposition had no impact on the obtained size of priming. In fact, there was no difference between the size of the priming effects in the morphologically related and the TL-across condition when compared to the substituted letter condition (Rueckl & Rimzhim, 2010, Experiment 2 & 3; *teacher-TEACH* vs. *teacifr-TEACH* and *teacehr-TEACH* vs. *teacifr -TEACH*). Interestingly however, the difference between the morphologically related and the TL-within condition (*teacher-TEACH* vs. *teakser-TEACH* and *teahcer-TEACH* vs. *teakser-TEACH*) *was* significant in Experiment 1, but *not* in Experiment 3.

The evidence reported by Rueckl and Rimzhim (2010) show that inconsistencies remain in morphological transposed-letter priming studies. While Christianson et al. (2005) and Duñabeitia et al. (2007) reported evidence for the disappearance of transposed-letter priming for across-boundary transpositions, Rueckl and Rimzhim demonstrate that this is not always the case. However, two points should be noted regarding the generalization of their findings. First, position-specific orthographic prime-target overlap was always greatest in the morphologically related condition (*teacher-TEACH*, 5 letter overlap), less in the across-morpheme boundary condition (*teacehr-TEACH*, 4 letter overlap) and lowest in the within-morpheme boundary condition (*teahcer-TEACH*, 3 letter overlap). It cannot therefore be ruled out that the largest priming effects found in the morphologically related condition relative to the TL-within condition were due to greater orthographic prime-target overlap as measured in terms of position-specific overlap. A second concern arises with the external position of letter transpositions (*teahc*). It is known that TL-nonwords with transpositions at external positions resemble their corresponding real word to a lesser degree than TL-nonwords with transpositions at internal positions (Johnson, Perea, & Rayner, 2007; Perea & Lupker, 2007; Rayner, White, Johnson, & Liversedge, 2006). It is possible that the involvement of external letters reduced the amount of priming observed in the TL-within condition. It is therefore important to establish whether this difference would also be obtained when (i) the amount of orthographic prime-target overlap is balanced across conditions and (ii) only internal letters of the stem are transposed.

We conducted two masked primed lexical decision experiments to further explore the role of transposed-letter manipulations in morphological processing, in Spanish. In particular, we were interested in directly comparing the magnitudes of the priming effects obtained for suffixed primes and TL-primes relative to an unrelated control, in order to gain a better understanding of the impact of letter transpositions in morphological processing. Our goal was to control for orthographic prime-target overlap by introducing an unrelated priming condition while transposing at internal positions of the stem morpheme only. We conducted two masked primed lexical decision experiments. Experiment 1 assessed the role of letter position coding in morphologically complex word processing in Spanish. Experiment 2 was designed to extend the findings from Experiment 1, in particular to investigate the influences of semantic factors in early morphological processing.

Experiment 1

TL-nonword primes were constructed from Spanish suffixed words (e.g. *dlooroso* from *doloroso* [*painful*]). Targets were made of the monomorphemic stems of these suffixed words (*DOLOR* [*pain*]). To guarantee that the transposed-letter similarity effect would not be reduced by the transposition of external letters (Johnson et al., 2007; Perea & Lupker, 2007; Rayner et al., 2006), transpositions were only performed with internal letters of the stem. Priming in the TL-conditions (*dlooroso-DOLOR*) was compared to a substituted-letter control (*dteoroso-DOLOR*). Furthermore, we used a morphologically related priming condition (*doloroso-DOLOR* [*painful-PAIN*]) and a fully unrelated word priming condition (*tumoroso-DOLOR* [*tumorous-PAIN*]).

If it is the case that morphological effects operate purely over *early* orthographic encoding mechanisms with high positional uncertainty (e.g. Longtin & Meunier, 2005; Rastle et al., 2004; Taft, 2003), no differences between the size of the priming effects for morphologically related primes and morphologically complex TL-primes (*doloroso-DOLOR* vs. *dlooroso-DOLOR*) should be observed, as measured against the unrelated word priming condition. That is, while some basic positional context is needed in order to recognize a morpheme, positional information is still underspecified at the time that morphological information is encoded. If however, morphologically complex words are decomposed at *later* stages in lexical processing with less positional uncertainty (e.g. Giraudo & Grainger, 2003; Marslen-Wilson, Tyler, Waksler & Older, 1994, see also Diependaele et al., 2009), *dlooroso* should prime *dolor* to a lesser degree than *doloroso*. That is, the magnitude of priming in the TL-condition should be reduced.

Method

Participants

Thirty-six undergraduate students from the University of the Basque Country participated in this study. All participants were native Spanish speakers and had normal or corrected-to-normal vision.

Materials

A set of 76 Spanish words was selected as targets (e.g., *dolor* [*pain*]; see Table 1 for characteristics). Each target could be preceded by four possible primes: a morphologically related prime (*doloroso* [*painful*], a transposed-letter prime (*dlooroso*), a replaced-letter control prime (*dteoroso*), or an unrelated prime (*tumoroso* [*tumorous*]). Related and unrelated prime words were matched on length, orthographic N, word frequency, bigram frequency, stem length, stem orthographic N, and stem frequency (see Table 1). In order to control for the potential impact of the suffix, the unrelated word selected for each related word prime always included the same suffix (*doloroso* and *tumoroso*). Transposed-letter nonword primes were created by transposing two internal letters of the stems (*dlooroso*). None of the transpositions included two vowels (see Lupker, Perea, & Davis, 2008), and none of the letter transpositions led to the creation of a real word (Duñabeitia, Molinaro, Laka, Estévez, & Carreiras, 2009; Duñabeitia, Perea, & Carreiras, 2009). The replaced-letter (RL) control condition was created by substituting the two transposed-letters with two new letter identities with a similar formal resemblance (*dteoroso*). Transposed and replaced-letter primes were matched on length, orthographic N, and bigram frequency (see Table 1). A complete list of stimuli is provided in Appendix 1.

For the purpose of the lexical decision task, we included a set of 76 nonword targets which were all orthographically legal and pronounceable by replacing the first and the last letter of a real word (e.g., the nonword *ozus* from the word *azul*). Each nonword target was preceded by four different primes, following the same conditions used for word trials (Morphologically related: *ozusado*; Transposed-letters: *ouzsado*; Replaced-letters: *oicsado*; Unrelated: *loctosado*).

Four lists were created, so that each target only appeared once in each list, but each time in a different priming condition. Nine participants were randomly assigned to each of the lists.

Table 1. *Mean word frequency, bigram frequency, length and orthographic N for the stimuli in Experiment 1, taken from Davis & Perea (2005).*

	Word frequency	Bigram frequency	Length	N
Targets	56.02	2.34	5.21	3.93
Related primes	9.58	2.32	7.70	0.88
TL-primes	--	1.83	7.71	0.17
RL-primes	--	1.78	7.71	0.14
Unrelated primes	6.78	2.37	7.63	0.92

Procedure

Stimuli were presented in the centre of a CRT computer screen using the DMDX display system (Forster & Forster, 2003) in randomised order. Each participant was tested individually in a quiet room located at the Basque Center on Cognition, Brain and Language. Each trial consisted of the presentation of a forward mask of # symbols for 500 ms, followed by the presentation of the prime in lowercase for 53 ms, and immediately followed by the presentation of the uppercase target stimulus. The target remained on the screen until the subject responded or for a maximum of 2500 ms. Participants were asked to decide as quickly and accurately as possible whether the visually presented targets were real Spanish words or not (i.e., a lexical decision task). Two keys of the keyboards were appropriately labelled. The whole experimental session lasted for about 10 minutes.

Results and Discussion

Reaction times longer than 1500 ms or shorter than 300 ms were discarded (18 outliers were identified, 0.7 % of the data). Mean reading latencies and error rates averaged over subjects are presented in Table 2.

RTs were transformed logarithmically and the main analyses were performed using linear mixed effect model modelling (e.g. Baayen, 2008; Baayen, Davidson, & Bates, 2008). To reduce the variance in the models, we included the predictor Trial Number as a measure of how far the participant has progressed into the experiment. This measure allows us to control for longitudinal task effects such as fatigue or habituation. Furthermore, since every participant was presented with items in a different random order, the order of trial presentation may have had different effects on individual subjects. Therefore, to adjust the by-subject random slopes for Trial Number, we included a correlation parameter specified in the random-effect structure of each subject (Baayen, 2008, pp. 251-252). A generalised linear mixed-effects model as implemented in the lme4 package (from http://cran.r-project.org/web/packages/) in the statistical software R (version 2.10.1, RDevelopmentCoreTeam, 2008) was used with two fixed effects factors (Trial Number and Prime Type: Related, Transposed-letter, Replaced-letter, Unrelated) and two random-effects factors (random intercepts for Subjects and Items). Factors were selected in a step-wise model selection procedure and only included when a formal comparison between models showed a significant improvement of the model's fit when the factor was added to the model. Significance was accessed with p-value sampling *pvals.fnc*, as implemented in the language R package (Baayen, 2008).

Table 2. *Mean lexical decision times (in ms) and percentage of errors for real word targets in Experiment 1. Standard deviations are shown in parentheses.*

Type of prime	Reaction times	Error rates
Related	647	5.0%
	(70)	(4.4%)
Transposed-letter	648	5.1%
	(61)	(4.6%)
Replaced-letter	664	5.3%
	(66)	(4.7%)
Unrelated	673	6.2%
	(73)	(5.8%)
TL-priming effect	25	0.2%
Morphological priming effect	26	1.2%

The model revealed that words preceded by morphologically related primes were responded to significantly faster than words preceded by unrelated primes (26 ms), $t = 4.3$, $p < .001$. Similarly, words in the transposed-letter priming condition were classified significantly faster than words preceded by unrelated primes (25 ms), $t = 4.0$, $p < .001$. The replaced-letter condition did not differ significantly from the unrelated condition (9 ms), $t = 1.5$, $p = .125$. No significant differences were obtained between the morphologically related and the transposed-letter priming condition, $t = 0.4$, $p = .704$. Critically, there was a significant difference between the replaced-letter priming condition and the morphologically related priming condition (17 ms), $t = 2.8$, $p = .005$. Similarly, the transposed-letter primes significantly facilitated target recognition as compared to replaced-letter primes (16 ms), $t = 2.4$, $p = .015$. None of the effects in the error rate analyses and in the nonword data were significant.

The results obtained in the present masked priming experiment can be summarized as follows: First, we replicated the well-known masked morphological priming effect using Spanish materials (*doloroso-DOLOR* vs. *tumoroso-DOLOR*). Second, a significant priming effect was also obtained for morphologically related primes that included a letter transposition within the stems (*dlooroso-DOLOR* vs. *tumoroso-DOLOR*). Third, the priming effect was no larger in the morphologically related condition (*doloroso-DOLOR*) than in the transposed-letter condition (*dlooroso-DOLOR*). Fourth, we replicated the transposed-letter priming effect, showing that targets preceded by transposed-letter primes were recognized significantly faster than targets preceded by primes including a letter replacement (*dlooroso-DOLOR* vs. *dteoroso-DOLOR*). And fifth, we showed that no signs of priming effects are found when two of the internal letters of the morphologically related primes are replaced by other letters, as compared to completely unrelated primes (*dteoroso-DOLOR* vs. *tumoroso-DOLOR*).

The key finding in this study was the lack of difference in the magnitude of the priming effects observed for the non-transposed morphologically related primes and the morphologically related primes that included a letter transposition within the stem (namely, for *doloroso-DOLOR* and *dlooroso-DOLOR*; 26 ms and 25 ms respectively, as compared to the unrelated primes, and 17 ms and 16 ms respectively as compared to the replaced-letter primes). The masked transposed-letter priming effect (Andrews, 1996; Forster et al., 1987; Perea, Duñabeitia, & Carreiras, 2008; Perea & Lupker, 2003; Peressotti & Grainger, 1999; Schoonbaert & Grainger, 2004) has been generally taken as clear-cut evidence in favor of models that assume imprecise initial coding of letter position (Grainger & van Heuven, 2003; Whitney, 2001). The present results confirm that masked morphological subset priming effects (*doloroso-DOLOR*) do also occur for nonword primes in which internal letters of the stem have been distorted by means of letter transpositions (*dlooroso-DOLOR*). Despite the increased complexity of the nonword string *dlooroso* (suffixed and TL-manipulated) as compared to the word *doloroso* (only suffixed, no TL-manipulation), no difference was found between the priming effects.

The present priming effects, are in line with Rueckl and Rimzhim’s Experiment 3 in English, which found equal amounts of morphological priming and within-boundary transposed-letter priming (*teacher-TEACH* vs. *teahcer-TEACH*). However, the present findings differ from Rueckl and Rimzhim’s Experiment 1 which showed significantly less within-boundary transposed-letter priming than morphological priming. Our results may have differed for the following two reasons. First, Rueckl and Rimzhim measured morphological priming and transposed-letter priming against a substituted-letter control. Therefore, since the position-specific orthographic prime-target overlap in the morphologically related condition was greater than in the transposed-letter and substituted-letter condition, the obtained effects may reflect an orthographic boost of priming for highly orthographically related prime-target pairs. Second, the decreased size of priming in the TL-within condition in Rueckl and Rimzhim's Experiment 1 may be attributed to the inclusion of external letter positions in within-boundary transpositions. Transposed-letter priming has been found to be less reliable for letter transpositions at external positions of a letter string (Johnson et al., 2007; Perea & Lupker, 2007; Rayner et al., 2006). However, more systematic investigations of internal versus external stem transpositions are needed to draw explicit conclusions.

In summary, the present results show that stem-target priming is equally obtained from both morphologically complex real words and morphological complex TL-nonwords. The virtually identical effect size in both conditions indicates that *dlooroso* and *doloroso* are practically the same at these early stages in visual word processing. This is inconsistent with the hypothesis that morphological decomposition effects are triggered at late processing stages (e.g. Giraudo & Grainger, 2003). If letter position coding had already had time to develop precise representations of positional information prior to the stem morpheme activation process, then the input string *dlooroso*, with high positional certainty, would prime *dolor* to a lesser extend than *doloroso*. The present data thus support the hypothesis that morphological processing operates with high positional uncertainty over early orthographic stages in visual word recognition (e.g. Longtin & Meunier, 2005; Rastle et al., 2004; Taft, 2003). This has critical implications for letter position encoding schemes indicating that the encoding of letter position and morphological information both occur at the same time, at early automatic word processing stages.

However, the evidence reported in Experiment 1 does not allow us to draw conclusions regarding the influences of semantics on morphological parsing. It is possible that morphological decomposition does not exclusively rely on morpho-orthographic encoding mechanisms and that the observed priming effects in Experiment 1 were at least partially driven by the morpho-semantic relationship between the prime and the target. There are thus two possible interpretations of the results. Since we only used primes which were either derived from real words (*dlooroso* or *dteoroso*) or were real words themselves (*doloroso* or *tumoroso*), it is not clear whether priming from *doloroso* or *dlooroso* to *dolor* occurred because of (a) early semantically 'blind' morpho-orthographic decomposition of *doloroso* into *dolor* or *dloor* and *oso* (Longtin & Meunier, 2005; Rastle & Davis, 2008) or (b) a combination of early morpho-orthographically and morpho-semantically guided parsing into morphemes (e.g. Diependaele et al., 2009; Feldman et al., 2009). The first hypothesis proposes that automatic affix-stripping occurs for all presented letter strings, based on purely structural information. Since this account predicts that early morphological processing stages operate solely on basis of orthographic analysis, priming to the stem would be expected to occur independently of the semantic prime-target relationship. The second hypothesis considers that morphological decomposition does not exclusively rely on morpho-orthographic encoding mechanisms and that the observed priming effects in Experiment 1 were at least partially driven by the morpho-semantic relationship between the prime and the target. Stem-target priming would therefore largely depend on the semantic transparency of morphemic subunits. Given that the primes in Experiment 1 were always words, these two hypotheses cannot be distinguished, as both hypotheses would predict the same pattern of effects from word primes. In order to understand to what extent the priming effects in Experiment 1 were affected by the semantic relatedness between prime and target, we designed Experiment 2 using suffixed nonword-primes.

Experiment 2

Based on a similar procedure as in Experiment 1, primes were now constructed by using lexically illegal stem-suffix combinations. Primes in all four conditions were created such that the whole prime did not have a lexical representation on its own (i.e., all primes were nonwords). Primes in the related condition were constructed from a Spanish stem morpheme (*total*) and a suffix (*ito*), and were followed by the stem target (*totalito-TOTAL*). In addition, we introduced a transposed-letter condition (*ttoalito-TOTAL*) with letter transpositions within the stem, and a replaced-letter control condition (*tfealito-TOTAL*). Finally, for every related prime we created an unrelated control prime by combining the same suffix (*ito*) with an orthographically unrelated stem of the same length (*sudorito-TOTAL*).

Due to the lack of semantic relationship between the stems and the whole primes (e.g. *total* has a meaning, but *totalito* does not), we significantly reduced the likelihood that any of the effects obtained in Experiment 2 could be driven by the semantic relationship between target and prime. The non-lexical nature of the primes allowed us to explore the influences of semantics on masked morphological priming. If morphological decomposition is purely based on orthographic analysis (e.g. Rastle et al., 2004; Taft, 2003) priming should occur independently of whether or not there is a semantic relationship between the prime and the target. We would thus expect priming to occur in the morphologically related condition (*totalito-TOTAL)* and in the transposed-letter condition (*ttoalito-TOTAL*). However, if morphological decomposition was triggered by a combination of morpho-orthographic and morpho-semantic factors (e.g. Diependaele et al. 2009; Feldman et al., 2009) priming in the morphologically related and in the TL-condition should be reduced or disappear.

Method

Participants

Forty undergraduate students from the University of the Basque Country participated in this study. All participants were native Spanish speakers and had normal or corrected-to-normal vision.

Materials

A set of 84 Spanish words was selected as targets (e.g., *TOTAL*; see Table 3 for characteristics). Each target could be preceded by four possible primes: a morphologically related prime (*totalito*), a transposed-letter prime (*ttoalito*), a replaced-letter control prime (*tfealito*), or an unrelated prime (*sudorito*). Related primes were created by combining stems (e.g. *total*) and suffixes (e.g. *ito*) such that the whole letter string would not make a word (e.g. *totalito* is not a word). All stem-suffix combinations were orthographically legal and pronounceable[1].

Related and unrelated nonword primes used the same suffixes and were matched on length, bigram frequency, orthographic N, stem length, stem orthographic N, and stem frequency (see Table 3). As in Experiment 1, transposed-letter nonword primes were created by transposing two internal letters of the stems (*ttoalito*). None of the transpositions included two vowels (see Lupker et al., 2008), and none of the letter transpositions led to the creation of a real word (Duñabeitia, Molinaro et al., 2009; Duñabeitia, Perea et al., 2009). The replaced-letter control condition was created by substituting the two transposed-letters with two new letter identities with a similar formal resemblance (*tfealito*). Transposed and replaced-letter primes were matched on length, orthographic N, and bigram frequency (see Table 3). A complete list of stimuli is provided in Appendix 2.

Table 3. *Mean word frequency, bigram frequency, length and orthographic N for the stimuli in Experiment 2, taken from Davis & Perea (2005).*

	Word frequency	Bigram frequency	Length	N
Targets	96.97	2.56	4.68	4.27
Related primes	--	2.0	8.0	0
TL-primes	--	1.67	7.68	0.04
RL-primes	--	1.68	7.68	0.04
Unrelated primes	--	2.0	8.0	0

[1] The selected stem-suffix combinations were either syntactically legal (e.g. *fusilote*; the suffix *ote* is typically attached to a noun, and *fusil* is a noun) or syntactically illegal (e.g. *exitodad*; the suffix *dad* is typically attached to an adjective, but *exito* is a noun).

For the purpose of the lexical decision task, we included a set of 84 nonword targets which were all orthographically legal and pronounceable by replacing the first and the last letter of a real word (e.g., the nonword *fotan* from the word *total*). Each nonword target was preceded by four different primes, following the same conditions used for word trials (Morphologically related: *fotanito*; Transposed-letters: *ftoanito*; Replaced-letters: *fdeanitio*; Unrelated: *sigacito*).

Four lists were created, so that each target only appeared once in each list, but each time in a different priming condition. Ten participants were randomly assigned to each of the lists.

Procedure

We followed the same procedure as in Experiment 1.

Results and Discussion

Reaction times longer than 1500 ms or shorter than 300 ms were discarded (28 outliers were identified, 0.9 % of the data). Mean reading latencies and error rates averaged over subjects are presented in Table 4.

Table 4. *Mean lexical decision times (in ms) and percentage of errors for real word targets in Experiment 2. Standard deviations are shown in parentheses.*

Type of prime	Reaction times	Error rates
Related	673	3.2%
	(65)	(4.5%)
Transposed-letter	682	3.0%
	(78)	(3.7%)
Replaced-letter	685	2.6%
	(71)	(3.7%)
Unrelated	685	3.5%
	(69)	(3.4%)
TL-priming effect	3	-0.4%
Morphological priming effect	12	0.3%

RTs were transformed logarithmically and the main analyses were performed using linear mixed effect model methodology as in Experiment 1. The model used had two fixed effects factors (Trial Number and Prime Type: Related, Transposed-letter, Replaced-letter, Unrelated) and two random-effects factors (random intercepts for Subjects and Items). Significance was assessed with p-value sampling *pvals.fnc*, as implemented in the language R package (Baayen, 2008).

The model revealed that words preceded by morphologically related primes were responded to significantly faster than words preceded by unrelated primes (12 ms), t = 2.0, p = .05. However, there was no significant difference between the transposed-letter priming condition and the unrelated condition (3 ms), t = 0.6, p = .459. The replaced-letter condition did not differ significantly from the unrelated condition (0 ms), t = 0.0, p = 1. No significant differences were obtained between the morphologically related and the transposed-letter priming condition (9 ms), t = 1.4, p = .162. There was a significant difference between the replaced-letter priming condition and the morphologically related priming condition (12 ms), t = 2.0, p = .04. There was no difference between the transposed-letter primes as compared to replaced-letter primes (3 ms), t = 0.6, p = .549. None of the effects in the error rate analyses and in the nonword data were significant[2].

The morphological priming effect obtained in Experiment 2 (*totalito-TOTAL* vs. *sudorito-TOTAL*) adds evidence to a growing body of studies showing that nonwords with an apparent polymorphemic structure are initially taken by the visual word recognition system as truly polymorphemic words. For instance, Meunier and Longtin (2007) showed that morphologically complex interpretable pseudowords effectively prime existing target words (*rapidifier-RAPIDE* [*quickify-QUICK*]) in masked priming. In a similar line, McCormick, Rastle and Davis (2009) have recently offered evidence showing that this is also the case in English. Our results confirm that morphologically complex Spanish nonword primes like *totalito* are also morphologically decomposed on the mere appearance of morphological complexity.

These findings are incompatible with full-listing accounts (e.g. Butterworth, 1983; Manelis & Tharp, 1977) that entirely reject the concept of morphological decomposition. Experiment 2 also provides evidence against post-lexical morphological processing theories (e.g. Giraudo & Grainger, 2003; Marslen-Wilson et al., 1994), as they assume that morphological decomposition is based on the prior activation of lexical representations and would therefore occur only for lexically represented letter strings. That is, they would predict the absence of priming effects for suffixed nonword primes such as *totalito-TOTAL*, and therefore cannot account for the observed pattern.

Interestingly however, no priming was obtained for nonword primes in which internal letters of the stem had been distorted by means of letter transpositions (*ttoalito-TOTAL*). That is, in contrast to the morphologically related condition, there was no evidence for a transposed-letter priming effect. However, it should be noted that the results for the comparison between

[2] A post-hoc factorial analysis revealed that the magnitude of priming in the related priming condition did not differ according to Syntactic Legality, t = 1.0, p = .317.

the morphologically related and transposed-letter condition were not entirely clear-cut, showing a statistically non-significant 9 ms difference. If it was truly the case that only morphologically related words produced priming, the morphologically related condition and the transposed-letter priming condition should have differed significantly. The strength of conclusions that can be drawn thus needs to be qualified in light of the absence of significance for this critical comparison. Most critically, however, the lack of masked transposed-letter priming effect proposes a challenge to purely morpho-orthographic processing accounts (e.g. Taft, 2003), which we discuss in more detail below.

General Discussion

The present experiments provide evidence for the morphological decomposition of affixed words and nonwords and affixed transposed-letter nonwords, and have important implications for models of morphologically complex written word recognition as well as theories of letter position coding. Experiment 1 investigated suffixed word primes and showed that morphologically complex primes without (*doloroso*) and with transpositions (*dlooroso*) equally facilitate participants' lexical decision response to the stem target (*DOLOR*). Experiment 2 extended this pattern of results to the domain of nonword primes showing that stem-target priming was only obtained in the morphologically related condition (*totalito*) but not in the transposed-letter condition (*ttoalito*).

The findings of Experiment 1 and 2 demonstrate that priming occurs with morphologically complex primes independently of whether stem and suffix do combine to a real word (*dolor* + *oso*) or not (*total* + *ito*). Since these results cannot be attributed to the semantic similarity of prime and target, one explanation of the results is to argue that the data are a reflection of orthographic relatedness. This explanation however seems highly unlikely given that numerous masked morphological priming studies have reported the absence of or inhibitory priming for orthographically related prime-target pairs with no shared morphology (*brothel-BROTH*; see Rastle & Davis, 2008, for a review of 14 related masked priming studies). In the present set of experiments, however, robust priming effects were obtained for morphologically related primes over an equivalent baseline. Hence, the former argument seems hard to make. We thus conclude that the present results are a reflection of the morphological relationship between prime and target supporting the view that morphological analysis occurs at a very early pre-lexical stage in word recognition (e.g. Taft & Forster, 1975; Rastle et al., 2004).

Our findings are incompatible with purely post-lexical accounts of the processing of written polymorphemic words (Giraudo & Grainger, 2001, 2003; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Plaut & Gonnerman, 2000). These accounts assume that decomposition is a semantically driven process that takes place once the whole word has been recognized in the lexicon (e.g. *full-listing* accounts; see Colé et al., 1989). If this were the case, no priming effects would have been observed for nonword primes such as *totalito-TOTAL*, since the nonsense string would not be listed in the lexicon, and therefore no morphological decomposition could occur for this type of primes, preventing morphological priming. Thus, although these accounts could predict priming effects for morphologically related prime words (*doloroso-DOLOR*) and for TL-manipulated real word primes (*dlooroso-DOLOR*) as used in Experiment 1, they would predict an absence of priming effects for suffixed nonword primes such as *totalito-TOTAL*, and therefore cannot account for the observed pattern. Hence, the present data converge with earlier masked morphological priming results (e.g. Meunier & Longtin, 2007; McCormick, Rastle, & Davis, 2009) showing that morphologically complex Spanish nonword primes like *totalito* are morphologically decomposed on the mere appearance of morphological complexity.

Taken together, Experiments 1 and 2 reveal important insights into how exactly readers access the internal structure of morphologically complex words. The priming effects found for suffixed real word primes (*doloroso-DOLOR*, Experiment 1) and for suffixed nonword primes (*totalito-TOTAL*, Experiment 2) confirm the hypothesis of an early automatic decomposition of strings with an apparent morphological structure (see Rastle et al., 2004), based on affix stripping mechanisms (e.g. Taft, 1979; Taft & Forster, 1975). On the basis of the presence of an affixed string, the visual word recognition system strips off the affix, starting a lexical search of the remaining letter chunk, independently of whether the whole string is a real word or not.

The findings in the TL-conditions however are not as clear-cut. While a significant TL-priming effect was found in Experiment 1 (*dlooroso-DOLOR*), there was no evidence for TL-priming in Experiment 2 (*ttoalito-TOTAL*). The observed difference cannot be explained by early letter position encoding accounts, because similarly to Experiment 1, the TL-stems in Experiment 2 (*ttoal*) only differed with respect to two letter positions to the target word (*total*). This difference also cannot be due to a morphological decomposition mechanism operating at the level of orthography, because both types of items equally comprise morpho-orthographic surface structures which the system would identify as formally identical. The differences must therefore be due to a mechanism originating from a different higher-level locus in the word recognition system.

Previous evidence suggests that the semantic interpretability of morphologically complex nonwords is taken into account at early processing stages (Diependaele et al., 2009; Feldman et al., 2009). In the present study, the semantic interpretability of the TL-nonwords differed across the two experiments. Given that the TL-nonwords used in Experiment 1 were created by transposing two letters in an existing letter string comprising a lexically legal combination of stems and suffixes (*doloroso*), readers could easily attach a meaning to the presented TL-nonword primes. The TL-nonwords in Experiment 2 however, were created by combining stems and suffixes such that the whole string was not a word (*totalito*), reducing the semantic interpretability of the letter string and inhibiting the reader's ability to attach a meaning to the presented nonword primes.

One explanation for the different results obtained in Experiment 1 and Experiment 2 may therefore be that the semantic interpretability of printed words affects early morphological processing stages. Thus, the priming of TL-nonwords like *dlooroso* obtained in Experiment 1 would not purely rely on the activation of the stem *dloor* (and *dolor* respectively) but also be partially driven by the semantic interpretability of the whole prime *doloroso*. The activation of *doloroso* through *dlooroso* would provide a boost to the activation of the morphemic sub-constituent *dolor* which would then in turn facilitate the TL-priming lexical decision response. In Experiment 2 however, the TL-prime *ttoalito* would not activate a whole prime, as the lexical representation for *totalito* does not exist. As compared to *dlooroso*, the processing of *ttoalito* would be lacking the same 'semantic boost' from the whole word level, and therefore purely rely on a morpho-orthographic processing mechanism, insufficient to produce TL-priming. Thus, the increased size of priming obtained for suffixed TL-nonwords in which the non-transposed whole string is a real word must origin from a different type of representational constraint within the word recognition system taking the semantic interpretability of the morphemic constituents into account.

In line with this interpretation, recent morphological decomposition accounts have proposed that meaning-relatedness contributes to masked morphological priming (e.g. Diependaele, Sandra, & Grainger, 2009; Feldman, O'Connor, & Moscoso del Prado Martin, 2009) suggesting that morphological decomposition does not exclusively rely on morpho-orthographic mechanisms (Duñabeitia, Kinoshita, Carreiras, & Norris, in press). Such accounts are primarily based on evidence showing increased priming effects for truly suffixed prime-target pairs (*cleaner-CLEAN*) as compared to pseudo-suffixed prime-target pairs (*corner-CORN*; the so-called *semantic transparency effect*; Diependaele et al., 2005). Effects of semantic-transparency indicate that there is a morpho-orthographic decomposition process which operates in a way such that every word bearing a true morphological structure (*cleaner*) or a morphological pseudo-structure (*corner*) is decomposed. However, the greater priming effects obtained for truly suffixed items suggest that there is a mechanism which takes into account the semantic or syntactic relationships between the lexical representations of prime and target. Although this difference has not always been significant in masked priming studies (see Rastle & Davis, 2008 for a review of 16 related masked priming studies), a numerical difference has almost always been observed. Particularly, it has been shown that semantic transparency effects in masked priming are more likely to be revealed with increased prime-target relatedness proportions (e.g. Feldman et al., 2009) and with procedures in which primes are partially or fully visible (e.g. Meunier & Longtin, 2007).

Further evidence for the co-occurrence of morpho-orthographic and morpho-semantic mechanisms in morphological decomposition comes from a set of masked priming studies by Diependaele et al. (2009) using cross-modal lexical decision, in English. In order to test the depth of the processing of the prime, the complexity of the prime was manipulated by comparing stem-primes (followed by derived targets) to derived-primes (followed by stem targets). The findings revealed that truly affixed (*rename-NAME*) and pseudo-affixed (*relate-LATE*) primes equally produced priming to their stem targets. However, when the prime-target order was reversed, significant priming was only obtained in the truly affixed condition (*name-RENAME*), whereas priming in the pseudo prefixed target condition completely disappeared (*late-RELATE*). It was concluded that, due to shorter length and higher frequency of stem-primes, they were processed more rapidly than their morphologically complex counterparts allowing the processing of the prime at a deeper semantic activation level. Thus, while Diependaele et al.'s results provide evidence for a decomposition mechanism operating at the level of orthography and decomposing any letter string bearing a morphological surface structure, there is clear support for a second decomposition procedure which takes into account the semantic relatedness between stem and whole word.

In light of these findings, the interpretation of the lack of TL-priming observed in Experiment 2 (*ttoalito-TOTAL*) seems straightforward. While the semantically transparent TL-nonwords in Experiment 1 (*dlooroso*) are experiencing feedback activation from the morpho-semantic parsing system, the semantically opaque TL-nonwords in Experiment 2 (*ttoalito*) do not benefit from higher-level semantic activations. In spite of the initially fuzzy encoding of the graphemes, the morpho-semantic system sends back reinforcing information helping to better establish and to reorder the position of the letters. The system will therefore process *dlooroso* based on the semantic coherence between the prime and the target, leading to nearly equal magnitudes of priming of *doloroso-DOLOR* and *dlooroso-DOLOR*. In the case of affixed TL-nonword primes like *ttoalito*, the feedback is so weak that it has limited influence on reordering processes. The lack of priming observed for TL-nonword primes with ungrammatical stem-suffix combinations (*ttoalito*) may therefore be attributed to the influences of higher-level processing mechanisms rather than entirely being due to decoding mechanisms operating at the level of orthography.

According to this account, it is also not surprising that the magnitude of morphological priming obtained in Experiment 1 (26 ms; *doloroso-DOLOR*) was numerically greater than that observed in Experiment 2 (12 ms; *totalito-TOTAL*). A word-prime like *doloroso* would be decomposed into its morphemic subunits, which would in turn activate their semantic features, so that then the combined meaning of the morphemic sub-constituents would strongly activate the existing representation of the whole word. Thus, a combination of a pre-lexical morpho-orthographic and a post-lexical morpho-semantic processing mechanism would lead to an increased activation of the stem morpheme *dolor*, producing priming. Similarly, a pre-lexical morphological parsing mechanism would decompose a nonword-prime like *totalito* into its morphemic sub-constituents, which would also activate their corresponding semantic features, producing priming. As opposed to *doloroso* however, the subunits *total* and *ito* do not combine to form a meaningful unit in the lexical system. That is, *totalito* would be purely decomposed on basis of an orthographic form analysis, which explains the relatively smaller size of priming observed in Experiment 2. Obviously, this involves drawing conclusions across experiments. A combined design would offer a more direct test for morphological parsing mechanisms underlying the processing of true morphological structures relative to morphologically complex nonword structures and provide a desirable extension of the present research.

An interesting way of teasing out further whether differences between the observed effects of priming were due to feedback from whole-word form activations or rather triggered by the semantic compatibility of stem and affix, would be to look at pseudo-structural transposed-letter nonwords (*nmuber-NUMB*). Pseudo-derivations make an interesting case, given that although the whole-string exists, the stem (*numb*) and the whole-word (*number*) are semantically incompatible. If the TL-priming differences in Experiment 1 and 2 were entirely morpho-semantic in nature, priming of *nmuber-NUMB* should be reduced. If however TL-priming was at least partially driven by the activation of pre-existing lexical form representations, *nmuber-NUMB* and *number-NUMB* should produce similar magnitudes of priming. Future research is needed to explore these alternatives.

In summary, our data suggest that morpho-orthographic parsing mechanisms benefit from semantic influences at early stages in the reading system, producing increased amounts of priming (*doloroso* or *dlooroso*), as compared to semantically non-interpretable (*totalito* or *ttoalito*) letter strings. The present semantic transparency effect obtained with non-transposed letter primes (*doloroso-DOLOR* vs. *totalito-TOTAL*) is consistent with models proposing an early semantically 'blind' morpho-orthographic segmentation stage (e.g. Rastle, Davis, & New, 2004; Taft, 2003; Taft & Nguyen-Hoan, 2010). These models suggest that semantic transparency effects arise at a later stage in the reading system, due to links between lexical form representations

(Taft & Nguyen-Hoan, 2010) or morpho-semantic activations of transparent derivations (Rastle & Davis, 2008). They predict, for example, that if the morpho-orthographic parsing system initially generates morphemic subunits that are semantically transparent (*doloroso*), then these processes will later benefit from higher-level semantic activations and thus produce additional priming in comparison to semantically opaque morpho-orthographically segmented letter-strings (*totalito*). However, it is more challenging to account for the pattern of TL-effects observed in the present set of studies in the context of these models. On the one hand one would expect significant transposed-letter priming to arise from both semantically transparent (*dlooroso*) and semantically opaque (*ttoalito*) TL-manipulated letter strings, which is inconsistent with the lack of masked transposed-letter priming in Experiment 2. However, it is also possible that initial morpho-orthographic processing is influenced by extremely rapid feedback from higher-level semantic processing stages, such that semantic constraints are able to influence letter reordering processing, which is not necessarily inconsistent with the idea that morphological processing stages are initially semantically blind.

Finally, the present work provides evidence for accounts postulating the simultaneous processing of morpho-orthographic and morpho-semantic information via two different pathways (e.g. Diependaele et al., 2009; Baayen et al., 1997; Feldman et al., 2009; Meunier & Longtin, 2007). The *hybrid model*, for instance, proposed by Diependaele et al. (2009), considers that any word possessing a true morphological structure (*doloroso* or *dlooroso*) is simultaneously decomposed via a (i) morpho-orthographic parsing route and a (ii) morpho-semantic pathway (after the activation of the whole word in the lexicon). Morphologically complex nonwords however (*totalito* or *ttoalito*) are parsed via the morpho-orthographic pathway only, given that the subunits *total* and *ito* do not form a meaningful unit in the lexical system. The hybrid model thus provides an explanation for the increased pattern of activation observed for lexically represented words as compared to non-existing letter strings.

In conclusion, the present masked priming letter transposition experiments demonstrate that morphologically structured words and nonwords are decomposed at early morpho-orthographic processing stages with high positional uncertainty. These Spanish data converge with evidence from other languages with morphologically complex structures, suggesting that morphological decomposition is a universal language-independent mechanism. The current studies further provide evidence for influences from higher-level processing stages to the morphological recognition system, suggesting that morpho-orthographic parsing mechanisms benefit from semantic constraints at early stages in the reading system. The exact mechanisms underlying morpho-orthographic and morpho-semantic mechanisms still remain to be explored.

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Appendix 1

Target	*related*	*TL*	*RL*	*unrelated*
COCHE	cochera	ccohera	crehera	guantera
FICHA	fichaje	fcihaje	fruhaje	ramaje
HACHA	hachazo	hcahazo	hrehazo	tortazo
GENTIL	gentileza	gnetileza	gmatileza	vileza
VARÓN	varonil	vraonil	vceonil	pastoril
OVAL	ovalada	oavlada	oeglada	redada
CABEZA	cabezazo	cbaezazo	cfuezazo	cañonazo
SUR	sureño	srueño	scieño	lugareño
AZAR	azaroso	aazroso	aesroso	sudoroso
HOGAR	hogareño	hgoareño	hjeareño	norteño
MELOCOTÓN	melocotonero	mleocotonero	mfaocotonero	relojero
MANCHA	manchada	mnachada	mrechada	riada
CERCA	cercano	crecano	ccacano	parroquiano
PODER	poderío	pdoerío	pfaerío	señorío
GUSTO	gustoso	gsutoso	gritoso	oloroso
NOVIA	noviazgo	nvoiazgo	nweiazgo	maestrazgo
PELO	pelona	pleona	pfaona	gritona
PAUSA	pausado	pasuado	pariado	reinado
ESPERANZA	esperanzador	epseranzador	egreranzador	pescador
PLUMA	plumaje	pulmaje	pitmaje	vendaje
GIGANTE	gigantesco	ggiantesco	gpuantesco	pintoresco
FÁBRICA	fabricante	fbaricante	fdericante	visitante
CONTAGIO	contagioso	cnotagioso	crutagioso	miedoso
POLICÍA	policíaco	ploicíaco	pfaicíaco	elegíaco
ARENA	arenal	aernal	aasnal	peral
PAJA	pajar	pjaar	pyear	telar
CRUEL	crueldad	cureldad	ciseldad	maldad
ÁNGEL	angelote	agneloten	aymeloten	machote
CALLE	callejón	clalejón	ctelejón	jarrón
ESPERA	esperable	epserable	egzerable	estimable
PESA	pesado	pseado	praado	vallado

HORA	horario	hroario	hzuario	rutinario
SEÑA	señal	sñeal	smoal	orinal
LEÑA	leñador	lñeador	lvoador	torturador
CARTEL	cartelera	cratelera	ccetelera	jabonera
ESTAFA	estafador	etsafador	efrafador	programador
DOLOR	doloroso	dlooroso	dteoroso	tumoroso
AZUL	azulado	auzlado	aislado	doctorado
BALÓN	balonazo	blaonazo	bfeonazo	fogonazo
LLAVE	llavero	lalvero	lekvero	traicionero
CAZA	cazador	czaador	cseador	marcador
CAMPEÓN	campeonato	cmapeonato	cnepeonato	patronato
POBRE	pobreza	pboreza	pdereza	grandeza
ÁGIL	agilidad	aiglidad	auplidad	igualdad
ALCOHOL	alcohólico	aclohólico	ardohólico	metálico
CAJÓN	cajonera	cjaonera	cyeonera	ratonera
LIMÓN	limonero	lmionero	lnuonero	refranero
BOCA	bocado	bcoado	bruado	trajeado
ABAD	abadesa	aabdesa	aeddesa	condesa
FERVOR	fervorosa	frevorosa	fzavorosa	dolorosa
ATRÁS	atrasado	artasado	asbasado	cruzado
BALCÓN	balconada	blaconada	bfeconada	puñalada
HABLA	hablador	hbalador	hdelador	tomador
ENGAÑO	engañoso	egnañoso	eymañoso	poroso
CALMA	calmante	clamante	ctemante	feriante
FANGO	fangoso	fnagoso	fmegoso	ruidoso
MISA	misal	msial	mzual	ventanal
BURLA	burlador	brulador	bsilador	luchador
CULPA	culpable	clupable	cfipable	loable
NOBLE	nobleza	nboleza	nfeleza	tristeza
IDEA	ideal	iedal	iabal	tribunal
PUDOR	pudoroso	pduoroso	pbioroso	amoroso
BILLETE	billetera	bliletera	bfuletera	papelera
BREVE	brevedad	bervedad	basvedad	levedad
DESEO	deseoso	dseeoso	dzaeoso	morboso

AMIGA	amigable	aimgable	aungable	rentable
BARNIZ	barnizado	branizado	bsenizado	ordenado
EDITOR	editorial	eidtorial	eubtorial	normal
JORNAL	jornalero	jronalero	jsunalero	mesonero
COPA	copazo	cpoazo	cgeazo	pantallazo
FIN	final	fnial	fmual	nacional
PALMA	palmada	plamada	ptemada	guarrada
ESPÍRITU	espiritual	epsiritual	egriritual	floral
LLANA	llanada	lalnada	lefnada	patada
FRUTA	frutal	furtal	fistal	rosal
PAR	pareja	praeja	pceeja	moraleja

Appendix 2

Target	*related*	*TL*	*RL*	*unrelated*
CAPA	capadad	cpaadad	cgeadad	retodad
RISA	risable	rsiable	rceable	finable
CONDE	condedor	cnodedor	cvadedor	mandodor
RIGOR	rigorato	rgiorato	ryeorato	hotelato
FOTO	fotoble	ftooble	fbaoble	roboble
CLIMA	climadad	cilmadad	cedmadad	juliodad
SEDE	sedetud	sdeetud	shaetud	mapatud
CIVIL	civilato	cviilato	cweilato	ordenato
CIMA	cimador	cmiador	cwuador	cunador
TOTAL	totalito	ttoalito	tfealito	sudorito
VINO	vinodad	vniodad	vreodad	gozodad
NUCA	nucatud	ncuatud	nriatud	murotud
HUMOR	humoresa	hmuoresa	hnioresa	mayoresa
RUBIO	rubiotud	rbuiotud	rfaiotud	marcatud
HOGAR	hogarito	hgoarito	hjearito	furorito
LICOR	licorido	lciorido	lreorido	virilido
SOLAR	solarajo	sloarajo	stuarajo	igualajo
CERO	cerotud	creotud	csaotud	filatud
MITAD	mitadano	mtiadano	mdeadano	gafasano
LUJO	lujoble	ljuoble	lgaoble	masable
CRUZ	crucesa	curcesa	concesa	amoresa
AZAR	azaraza	aazraza	aesraza	oloraza
PELO	pelotud	pleotud	pfiotud	purotud
VALOR	valorico	vlaorico	vteorico	robotido
GORDO	gordoble	grodoble	gsudoble	golpeble
LOCAL	localura	lcoalura	lrialura	canalura
USTED	ustedano	utsedano	ulnedano	finalano
TEST	testona	tsetona	tritona	edadona
FRUTO	frutoble	furtoble	fastoble	chinoble
TUMBA	tumbable	tmubable	twobable	aldeable
ÉXITO	exitodad	eixtodad	euwtodad	eticadad

ÁRABE	arabedad	aarbedad	aecbedad	partodad
RIVAL	rivalavo	rvialavo	rnealavo	autoravo
SEÑOR	señorazo	sñeorazo	sziorazo	dosisazo
TUMOR	tumorido	tmuorido	twaorido	fugacita
GRIS	grisano	girsano	gensano	granano
BEBÉ	bebedad	bbeedad	bduedad	bajodad
AZUL	azulano	auzlaja	aoslaja	ayerano
FEROZ	ferozura	freozura	fcaozura	calorura
CASA	casadad	csaadad	croadad	votodad
FLOR	floraje	folraje	fedraje	tresaje
CINCO	cincotud	cnicotud	cvecotud	playatud
JUNIO	juniodor	jnuiodor	jvaiodor	normador
MORAL	moralona	mroalona	msealona	abrilona
PODER	poderato	pdoerato	pbaerato	altarato
METAL	metaleña	mtealeña	mbialeña	atraseña
PLOMO	plomodor	polmodor	petmodor	bolsador
TENOR	tenorona	tneorona	tsuorona	balonona
LEJOS	lejosajo	ljeosajo	lgaosajo	comunajo
VIRUS	viruseza	vriuseza	vseuseza	luneseza
IDEAL	idealeña	iedaleña	iutaleña	anteseña
TESIS	tesisaza	tseisaza	troisaza	señalaza
OESTE	oestedad	osetedad	ozatedad	drogadad
JUSTO	justodad	jsutodad	jzitodad	climadad
CARO	carodad	craodad	cniodad	sumadad
AHORA	ahorable	aohrable	aufrable	pobreble
MENOS	menosaja	mneosaja	mraosaja	favoraja
RELOJ	relojano	rleojano	rbuojano	fatalano
MOTOR	motorosa	mtoorosa	mleorosa	cañonosa
PLANO	planodor	palnodor	peknodor	polvodor
BATA	batable	btaable	bdeable	balable
JOVEN	joveneño	jvoeneño	jcaeneño	facileño
ENERO	enerotud	eenrotud	eazrotud	tributud
GOTA	gotatud	gtoatud	gleatud	ascotud
TÚNEL	tunelavo	tnuelavo	tsielavo	lugaravo

MEJOR	mejorero	mjeorero	myaorero	honorero
CULO	culodor	cluodor	cfiodor	rojodor
SALUD	saludeza	slaudeza	sboudeza	coloreza
PLAN	planeño	palneño	putneño	golfeño
SOCIO	sociotud	scoiotud	sreiotud	barratud
PLAZA	plazatud	palzatud	pedzatud	geniotud
DEDO	dedodor	ddeodor	dkaodor	artedor
TUBO	tuboble	tbuoble	tleoble	actoble
MUSEO	museoble	msueoble	mcieoble	nadieble
NIVEL	nivelona	nvielona	nsaelona	cruelona
TEXTO	textodor	txetodor	tzitodor	rollodor
HIJO	hijoble	hjioble	hyeoble	vagoble
MENOR	menorita	mneorita	msaorita	semenita
RUMOR	rumorico	rmuorico	rneorico	laborico
MANO	manodad	mnaodad	mveodad	coladad
VAPOR	vaporeño	vpaoreño	vgeoreño	teniseño
MUJER	mujeraje	mjueraje	myoeraje	capazaje
FUSIL	fusilote	fsuilote	freilote	adiosote
VITAL	vitalaje	vtialaje	vbealaje	legalaje

Morphological processing during visual word recognition in developing readers: Evidence from masked priming.

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Abstract

Masked priming studies with adult readers have provided evidence for a form-based morpho-orthographic segmentation mechanism which 'blindly' decomposes any word with the appearance of morphological complexity. The present studies investigated whether evidence for structural morphological decomposition can be obtained with developing readers. We used a masked primed lexical decision design first adopted by Rastle, Davis, and New (2004), comparing truly suffixed (*golden-GOLD*) and pseudo-suffixed (*mother-MOTH*) prime-target pairs with non-suffixed controls (*spinach-SPIN*). Experiment 1 tested adult readers, showing that priming from both pseudo- and truly suffixed primes could be obtained using our own set of high-frequency word materials. Experiment 2 assessed a group of Year 3 and Year 5 children, but priming only occurred when prime and target shared a true morphological relationship, and not when the relationship was pseudo-morphological. This pattern of results indicates that morpho-orthographic decomposition mechanisms do not become automatized until a relatively late stage in reading development.

Keywords: visual word recognition, masked priming, lexical decision, morphological decomposition, reading development

Morphological processing during visual word recognition in developing readers: Evidence from masked priming.

While the recognition of a morphologically simple written word such as *walk* involves the mapping of the letters *w-a-l-k* onto higher-level lexical and semantic representations, the mapping of a morphologically complex word like *walked* entails more complex recognition mechanisms to also identify the word's morphological features (e.g. *walk* [Verb] + *ed* [past tense]). Morphological knowledge is a critical skill in language processing and language acquisition as it requires the understanding of linguistic concepts such as plural formations (e.g. *tree-s*), grammatical person information (e.g. *walk-s*), and past tense formations (e.g. *walk-ed*). There is much still to be learned about the mechanisms children use to access this knowledge when processing morphologically complex written words and what the developmental milestones are in the acquisition of these mechanisms.

Previous studies investigating morphological processing of written words in developing readers have demonstrated that children show evidence of sensitivity to morphological structure from a young age, as early as five years old (Treiman & Bourassa, 2000; Treiman & Cassar, 1997). Influences of morphological knowledge have been demonstrated on word reading accuracy (e.g. Carlisle & Katz 2006; Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009) and on written vocabulary knowledge (e.g. Bertram, Laine, & Virkkala, 2000; Wysocki & Jenkins, 1987), but the largest body of research has used spelling tasks to study written morphological knowledge development (e.g. Carlisle, 1988; Deacon & Bryant, 2006a; Kemp & Bryant, 2003). For instance, Carlisle (1988) reported that, while Year 4 and Year 6 children produced more accurate spellings of morphologically complex word forms (*teacher*) if they could also correctly spell the stem morpheme (*teach*), they very rarely spelled a derived form correctly when they had also misspelled the corresponding stem. These results show the influence of morphological cues on spelling performance and indicate that the spelling of derived forms is based on knowledge of morphological relationships (see also Deacon & Bryant, 2005, 2006a; Kemp & Bryant, 2003; Rubin, 1988; Treiman & Cassar, 1996).

Moreover, Deacon and Bryant (2006b) have reported that these findings do not appear to be attributable to orthographic overlap between derived forms and their stems. They compared a set of morphologically complex words (*turning*) consisting of a stem morpheme (*turn*) and a suffix (*ing*) to a matched set of morphologically simple control words (*turnip*) in which the first letters were identical to the stem (*turn*), but followed by a non-morphological ending (*ip*). Year 3 to Year 5 children were asked to fill the gap in a sentence in which the stem morpheme *turn* was either presented as a clue (e.g. '*We had to turn the car before __ into the lane*.' [*turning*]) or was not presented as a clue (e.g. '*She was in charge of __ the pages*.' [*turning*]). The results showed that children made fewer errors on spelling the first morphemic sequence (*turn*) when it was part of a morphologically structured target word (*turning*) as compared to when there was non-morphological orthographic relationship between the stem and the target (*turnip*), thus suggesting that the children's enhanced performance on the morphological awareness task was not simply due to their ability to match orthographically related letter strings.

In summary, there is evidence for children's ability to identify morphological substructures in printed words from a relatively young age (for further review, see Bryant & Nunes, 2008; Carlisle, 2003; Deacon, 2008; Pacton & Deacon, 2008). However, given that most of these studies drew upon data from production tasks, they cannot directly address the question of when and how morphological information is processed during visual word recognition in developing readers. Moreover, since children's responses in these kinds of tasks may be open to explicit processing and to strategic factors, they are less able to provide insight into the automatic processing of morphologically complex written words by children during reading.

The present study was designed to investigate morphological processing during visual word recognition in young readers and, specifically, to test at what level of reading development morphological processes become automatized. To do so, we drew upon the masked priming paradigm, which has been widely used to explore non-strategic processes in complex word recognition in adults (Longtin, Segui, & Hallé, 2003; Rastle, Davis, Marslen-Wilson, & Tyler, 2000). A typical masked priming experiment comprises a sequence of events which are presented as follows: first, a forward mask is presented for approximately 500 ms consisting of a string of non-lexical symbols, typically hash keys. The forward mask is then followed by a briefly presented stimulus (typically shown for 40-70 ms), the so-called prime, which is then immediately replaced by another stimulus, the target. The presentation of the target lasts until the participant's response. Although participants are typically not aware of the existence of the masked prime, facilitatory and inhibitory influences on target performance can be measured, thus providing a window into early, automatic processes in visual word recognition (Forster & Davis, 1984; Forster, Davis, Schoknecht, & Carter, 1987).

One of the most influential studies of masked morphological priming in adults was conducted by Rastle and colleagues (2004). Rastle et al. propose a morphological segmentation process that operates on basis of orthographically defined morphological units such that every item bearing a morphological structure is decomposed, regardless of whether the stem and the whole word are semantically related or not (see also Longtin et al., 2003 for related evidence in French). Rastle et al. carried out a masked primed lexical decision experiment comparing prime-target pairs sharing either a true morphological (*golden-GOLD*) or a pseudo-morphological (*mother-MOTH*) relationship to a non-morphological control condition (*spinach-SPIN*). In the first condition, stems were preceded by *truly suffixed* primes, in which the meaning of the whole word (*golden*) could be derived from the meaning of its morphemic subunits (*gold* + *en*). Secondly, a set of *pseudo-suffixed* primes was chosen (*mother*) with a meaning unrelated to the meaning of its stem morpheme (*moth*). Finally, *non-suffixed* primes were selected such that there was an orthographic overlap between the prime (*spinach*) and the target (*spin*), while the word endings were exclusively non-morphemic (*ach*). None of the non-suffixed primes and targets was related in meaning. Primes were presented in lowercase for 42 ms preceded by a 500 ms forward mask and followed by the targets presented in uppercase.

The results showed a significant priming effect for both truly affixed (*golden-GOLD*) and pseudo-suffixed (*mother-MOTH*) prime-target pairs, but not in the non-morphological control condition (*spinach-SPIN*). Moreover, the amount of priming obtained in the truly suffixed condition (27 ms) did not differ from that obtained in the pseudo-suffixed condition (22 ms). This suggests that, in skilled adult readers, priming occurs 'blindly' for any stimulus with a *morpho-orthographic* surface structure, and that the observed effects of morphological decomposition are not controlled by the semantic or syntactic relationship between the lexical representations of prime and target. In addition, the lack of priming in the non-suffixed condition indicates that the obtained priming effects are not just due to orthographic overlap between the prime and the target.

Rastle et al.'s (2004) findings have been replicated and extended across various languages (e.g. Diependaele, Sandra, & Grainger, 2005 [Dutch and French]; Duñabeitia, Perea, & Carreiras, 2007 [Spanish and Basque]; Longtin & Meunier, 2005 [French]) suggesting that semantically blind morphological decomposition provides a universal mechanism by which skilled readers rapidly and automatically detect morpho-orthographic surface structure. More recently, morphological processing accounts have extended Rastle et al's results to suggest that morphological decomposition does not exclusively rely on morpho-orthographic segmentation mechanisms. Such accounts are primarily based on evidence showing increased priming effects for truly suffixed prime-target pairs (*golden-GOLD*) as compared to pseudo-suffixed prime-target pairs (*mother-MOTH*). Although a majority of masked priming studies investigating true versus pseudo-morphological relationships have failed to reveal semantic transparency effects (for a review, see Rastle & Davis, 2008), it has been shown that the degree of *morpho-semantic* influence on priming increases substantially when the presented prime becomes fully or partially visible (Marslen-Wilson, Tyler, Waksler, & Older, 1994; Meunier & Longtin, 2007; Rastle et al., 2000).

In recent years, the interplay of morpho-orthographic and morpho-semantic priming effects in skilled readers has been widely debated (see Davis & Rastle, 2010; Diependaele, Sandra, & Grainger, 2009; Feldman, O'Connor, & Moscoso del Prado Martin, 2009; Rastle & Davis, 2008) and three different classes of theories have been proposed. The first class of theory considers that any input letter string is always initially mapped onto early morpho-orthographic representations, whereas morphemic segmentation based on semantic analysis only occur at a later stage during word recognition (*form-then-meaning accounts*, hereafter; Rastle & Davis, 2008; Taft, 2003). The second class of theory postulates that morphemic units are uniquely recognised on basis of morpho-semantic decomposition mechanisms (*supra-lexical decomposition accounts*; Giraudo & Grainger, 2003; Marslen-Wilson et al., 1994). And the third class of theory predicts that both morpho-orthographic and morpho-semantic decomposition simultaneously occur in the context of a parallel dual-route model (*parallel dual-route accounts*; Baayen, Dijkstra, & Schreuder, 1997; Diependaele et al., 2009; see also Feldman et al., 2010).

Despite this extensive body of research in adults, relatively little work has used masked priming to examine morphological processing during visual word recognition in children. While several studies have demonstrated that masked priming effects can indeed be shown in children and that these can be used to investigate automatic non-strategic word recognition processes (Castles, Davis, Cavalot, & Forster, 2007; Castles, Davis, & Letcher, 1999; Pratarelli, Perry, & Galloway, 1994), this procedure has only recently begun to be applied to the domain of morphological reading development.

The one study that has taken this approach to date is one in French by Casalis, Dusautoir, Colé and Ducrot (2009), who examined masked morphological priming in Year 4 readers. In the context of a lexical decision task, morphologically complex targets, presented in lowercase, were preceded by uppercase primes that were either truly suffixed (*LAVEUR-lavage* [*CLEANER-washing*]), non-suffixed (*LAVANDE-lavage* [*LAVENDER-washing*]), or unrelated (*MOUTARDE-lavage* [*MUSTARD-washing*]). The primes were presented for durations of either 75 ms or 250 ms. In the 75 ms prime condition both truly suffixed and non-suffixed primes equally produced priming relative to the unrelated control condition. However, in the 250 ms conditions, there was significantly more priming in the truly suffixed than in the non-suffixed condition. These findings were taken to suggest that, while morphological and orthographic priming cannot be distinguished at shorter prime presentation durations (75 ms), morphological activation begins to be present with longer prime exposures (250 ms).

However, Casalis et al. (2009) did not include a pseudo-suffixed control condition of the kind used in Rastle et al. (2004), and so no conclusions can be drawn about the existence of a structural morphological decomposition mechanism in developing readers. As well, a 250 ms prime duration such as they used, and even a 75 ms duration, would generally be considered too long to allow exploration of rapid, automatic word recognition mechanisms. It thus remains uncertain at what point in reading development children might establish an automatic morphological parsing system, and what factors might influence this acquisition process. The present study was designed to address these issues. We replicated Rastle et al.'s design in a group of adults and two groups of developing readers, comparing truly suffixed (*golden-GOLD*), pseudo-suffixed (*mother-MOTH*) and non-suffixed (*spinach-SPIN*) prime-target pairs in a masked primed lexical decision task. In order to maximize the likelihood that the presented materials would be in the children's sight vocabulary, all prime and target items were highly frequent words extracted from a children's printed word database.

We conducted two masked primed lexical decision experiments. A group of adult participants was initially tested to explore if effects of semantically 'blind' structural morphological decomposition, typically obtained with skilled readers, occur with this new set of highly frequent printed word materials (Experiment 1). We then assessed two age groups of developing readers: Year 3 and Year 5 (Experiment 2).

Experiment 1

Experiment 1 was designed to test masked morphological priming in a group of skilled readers comparing truly suffixed (*golden-GOLD*), pseudo-suffixed (*mother-MOTH*) and non-suffixed primes (*spinach-SPIN*). The aim was to test whether significant stem-target priming can be obtained from pseudo-suffixed and truly suffixed primes, as evidenced in previous findings (Longtin & Meunier, 2005; Rastle et al., 2004), using our own materials. If there was priming in the pseudo-suffixed and truly suffixed conditions, this would provide evidence in support of a morpho-orthographic segmentation mechanism operating over any letter string with the mere appearance of morphological complexity. That is, the mere presence of pseudo-suffixed priming, regardless of whether or not the magnitude of truly suffixed priming was greater than the magnitude of pseudo-suffixed priming, would confirm that there is at least one component in the morphological parsing system which operates on the basis of orthographic analysis, independently of semantics. If priming were to be found in both pseudo-suffixed and truly suffixed conditions, but the facilitation was greater in the truly suffixed condition, this would provide support for an additional influence of semantic transparency on morphological processing.

Method

Participants

Thirty-two Macquarie University students participated for course credit or monetary reimbursement. All participants were native English speakers and had normal or corrected-to-normal vision.

Materials and Procedure

Masked Primed Lexical Decision Task. A set of 102 target words and 102 prime words was selected from the Essex Children's Printed Word Database (http://www.essex.ac.uk/psychology/cpwd). Each target was paired with a prime. The set of prime-target pairs was then divided into three different sub-sets of 34 pairs each. The first set of *truly suffixed* items was chosen such that the meaning of the prime could always be derived from the meaning of its stem-target (*golden-GOLD*). The items contained a mix of derived and inflected affixes and the effect of this factor was examined in post-hoc analyses. The *pseudo-suffixed* primes did not share a semantic relationship with the target, but comprised a morpho-orthographic surface structure (*mother-MOTH*). In the *non-suffixed* control condition, primes and targets were selected such that the relationship was purely orthographic (*spinach-SPIN*).

The stimuli matching criteria were adapted from Rastle et al. (2004). All three conditions were matched on orthographic overlap (calculated by dividing prime length by target length), target neighbourhood size, target length, target frequency, prime neighbourhood size, prime length, and prime frequency (see Table 1 for characteristics). The effect of target frequency was examined in post-hoc analyses. In addition, semantic relatedness values for each prime-target pair in all three conditions were extracted from Latent Semantic Analysis Web facility (http://lsa.colorado.edu) which revealed that semantic relatedness values in the truly suffixed condition (.51) were significantly higher than in both the pseudo-suffixed [.13; $t(48) = 9.48$] and the non-suffixed condition [.16; $t(47) = 8.74$], but the pseudo-suffixed and non-suffixed conditions did not differ [$t(66) < 1$].

For each target, an orthographically, morphologically and semantically unrelated control prime was selected from the Essex Children's Printed Word Database (*frosty-GOLD, greedy-MOTH, magical-SPIN*), which was matched to the related primes on frequency and length. Given that each target word was paired with two different types of primes (related and unrelated), two lists were created so that each target only appeared once in each list, but each time in a different priming condition. Participants were allocated to one of the two lists, such that they only ever saw any target once. A full list of stimuli is provided in Appendix 1.

In line with Rastle et al. (2004), an additional set of 34 unrelated word pairs was included to further reduce the prime-target relatedness proportion. The related and unrelated prime-target pairs were matched on target length. Finally, for the purpose of the lexical decision task, we included a set of 102 nonword targets (*CEBB*) which were all orthographically legal and pronounceable and matched on length to the real word targets. Each nonword target was preceded by morphologically complex word prime (*jumping-CEBB*).

Table 1. *Mean word frequency, neighbourhood size, length, and orthographic overlap for the stimuli in Experiment 1 and 2, taken from the CELEX database (Baayen et al., 1993). Standard deviations are shown in parentheses.*

Properties	Truly suffixed	Pseudo-suffixed	Non-suffixed
Targets			
Logarithmic word frequency	1.82 (0.47)	1.86 (0.84)	1.86 (0.82)
Neighbourhood size	8.97 (4.74)	8.82 (5.43)	9.97 (5.29)
Length, in letters	3.59 (0.66)	3.91 (0.71)	3.68 (0.59)
Primes			
Logarithmic word frequency	1.38 (0.60)	1.61 (0.73)	1.32 (0.73)
Neighbourhood size	2.94 (1.95)	2.26 (2.14)	2.71 (3.19)
Length, in letters	5.71 (0.63)	5.74 (0.93)	5.47 (0.9)
Orthographic prime-target overlap	1.63 (0.25)	1.48 (0.20)	1.51 (0.25)

Stimuli were presented in Courier New 12pt in the centre of a CRT computer screen, using the DMDX display system (Forster & Forster, 2003). Each trial consisted of a 500 ms forward mask of hash keys presented in the centre of the screen, followed by a 50 ms prime in lowercase, and immediately followed by the uppercase target. The number of hash keys was matched with the number of letters of the prime. Following Rastle et al.'s (2004) design, target words were presented individually and were not embedded into flanking symbols (e.g. %%TARGET%%). Rather than the 40 ms prime duration used by Rastle et al. (2004), we presented the primes for an extra 10 ms in order to allow sufficient stimulus processing time for developing readers. Prime durations of this length have been most standardly used in previous developmental priming studies (Castles et al., 2007 [50 ms]; Castles et al., 1999 [50 ms]; Pratarelli et al., 1994 [57 ms]). The target remained present until the subject responded or until a maximum delay of five seconds had elapsed. The participants used a response box with one button for the positive and one for the negative lexical decision response, and were instructed to respond as quickly and accurately as possible. The trials were presented in randomised order including a break in the middle. Eight practice trials were presented at the beginning of the session. The experiment took approximately 10 minutes to complete.

Results

Response latencies for incorrect responses for the primed lexical decision task were collected and removed (7.3% of the data). No subjects were discarded as all error rates were below 40%. Furthermore, different trimming procedures were tried (e.g. Standard Deviation Trimming and

Absolute-Value Trimming), but they did not change the size and the direction of the main effects and interactions.

The main data analyses were performed using linear mixed effect modeling (Baayen, 2008; Baayen, Davidson, & Bates, 2008). Response latencies were transformed logarithmically and significance was assessed with Markov chain Monte Carlo (MCMC) sampling, as implemented in the language R package (Baayen, 2008). In models integrating by-subject random slopes for Trial Number the computation of MCMC sampling could not be applied. Significance was therefore assessed with p-value sampling taking into account the upper bound for the degrees of freedom by subtracting the number of fixed-effect factors from the number of observations (Baayen, 2008; p. 248). Only those random effects are presented below that significantly improved the model's fit in a stepwise model selection procedure.

To reduce the variance in the models, we included the predictor Trial Number, a measure of how far the participant has progressed into the experiment. This measure allows us to control for longitudinal task effects such as fatigue or habituation. Furthermore, since every participant was presented with items in a different random order, the order of trial presentation may have had different effects on individual subjects. Therefore, to adjust the by-subject random slopes for Trial Number, we included a correlation parameter specified in the random-effect structure of each subject (Baayen, 2008, pp. 251-252) and centred the data to eliminate spurious correlations between across subject slopes and Trial Number (Baayen, 2008, pp. 254-255). The results for adults are presented in Table 2.

A generalised linear mixed-effects model as implemented in the lme4 package (from http://cran.r-project.org/web/packages/) in the statistical software R (version 2.10.1, RDevelopmentCoreTeam, 2008) was fitted with four fixed effects factors (Trial Number, Prime Type: Related vs. Unrelated, Item Type: Truly Suffixed vs. Pseudo-suffixed vs. Non-suffixed, and the interaction between Prime Type and Item Type) and two random-effects factors (random intercepts for Subjects and Items). The linear mixed-effects model estimates pair-wise level-by-level analyses for fixed-effects factor analyses yielding three Prime Type by Item Type comparisons. The latency data revealed a significant interaction of Prime Type and Item Type (i) across truly suffixed and non-suffixed trials, t = 6.37, p < .001, (ii) across pseudo-suffixed and non-suffixed trials, t = 2.49, p = .01, and (iii) across truly suffixed and pseudo-suffixed trials, t = 3.83, p < .001[3]. There were no significant interactions in the error data.

[3] To confirm the present findings, we performed analyses of variance (ANOVAs) of the latency data, by subject (collapsed across item data, reported as F1) and by item (collapsed across subject data, reported as F2), with the two factor Item Type (Truly Suffixed vs. Pseudo-suffixed vs. Non-suffixed) and Prime Type (Related vs. Unrelated). The analysis revealed a significant main effect of Item Type, $F_1(2, 30)$ = 13.82, p < .001, and $F_2(2, 32)$ = 6.35, p = .005, and a significant interaction of Item Type with Prime Type, $F_1(2, 30)$ =

To follow-up the pattern of interactions obtained in the combined analysis, three separate generalised linear mixed-effects models were fitted for each Item Type (Truly Suffixed, Pseudo-suffixed and Non-suffixed), with two fixed effects factors (Trial Number and Prime Type: Related vs. Unrelated) and two random-effects factors (random intercepts for Subjects and Items). These analyses revealed a significant priming effect in the Truly Suffixed condition, $t = 7.64$, $p < .001$, and in the Pseudo-suffixed condition, $t = 2.06$, $p = .04$. No priming was obtained in the Non-suffixed condition, $t = 1.56$, $p = .12$. No other effects were significant. The effects in the error data were not significant.

Table 2. *Mean lexical decision times and error rates for word targets averaged across adult participants (Experiment 1). Standard deviations are shown in parentheses.*

Condition	Reaction times	Error Rates	Example
	Truly suffixed		
related	504 (74)	4.2 (7.9)	*golden-GOLD*
unrelated	547 (77)	3.9 (6.6)	*frosty-GOLD*
priming effect	43	-0.4	
	Pseudo-suffixed		
related	535 (69)	9.6 (8.7)	*mother-MOTH*
unrelated	546 (80)	9.0 (9.3)	*greedy-MOTH*
priming effect	10	-0.5	
	Non-suffixed		
related	565 (118)	8.7 (7.6)	*spinach-SPIN*
unrelated	544 (68)	8.6 (7.6)	*magical-SPIN*
priming effect	-22	0	

Since significant priming effects were obtained in both the Truly Suffixed and the Pseudo-suffixed condition, we carried out an additional analysis across truly and pseudo-suffixed items using a generalised linear mixed-effects model with four fixed effects factors (Trial Number, Prime Type: Related vs. Unrelated, Item Type: Truly Suffixed vs. Pseudo-suffixed, and the interaction between Prime Type and Item Type) and two random-effects factors (random intercepts for Subjects and Items). The analysis revealed that truly suffixed trials were responded to faster than pseudo-suffixed trials, $t = 3.65$, $p < .001$. There was a significant main effect of Prime Type, $t = 1.92$, $p = .05$, and a

12.46, $p < .001$, and $F_2(2, 32) = 9.67$, $p < .001$. The main effect of Prime Type was significant in the subject data, $F_1(1, 31) = 4.38$, $p = .045$, but not in the item data, $F_2(1, 33) = 2.88$, $p = .1$.

significant interaction of Prime Type and Item Type, t = 4.04, p < .001. No other effects were significant. The error analysis showed that participants made fewer errors classifying truly suffixed words than pseudo-suffixed words, t = 2.69, p = .01. No other effects were significant.

Finally, to investigate whether there was an influence of target frequency and type of affixation (inflected or derived) on the observed effects priming, we performed post-hoc analyses collapsing across truly suffixed and pseudo-suffixed trials. The analyses revealed a marginally significant positive correlation between amount of priming and logarithmic target frequency, r = .226, t = 1.91, p = .06, but there was no significant correlation between amount of priming and type of affixation, r = .087, t = 0.49, p = .62.

Discussion

The results obtained in Experiment 1 revealed significant facilitation from both truly suffixed (*golden-GOLD* vs. *frosty-GOLD*) and pseudo-suffixed primes (*mother-MOTH* vs. *greedy-MOTH*) showing that priming occurred both when there was and when there was not a semantically transparent relationship between the prime and target. The significant priming in the pseudo-suffixed condition adds evidence to a growing body of research showing that there is a semantically blind morphological segmentation mechanism which decomposes any letter string with the mere appearance of morphological complexity. Critically, no priming was observed in the non-suffixed condition (*spinach-SPIN* vs. *magical-SPIN*), showing that the obtained effects of priming were not simply due to orthographic prime-target overlap.

In addition, there was a difference between the observed magnitude of priming in the truly suffixed condition relative to the pseudo-suffixed condition (43 ms vs. 10 ms). This differs from Rastle et al.'s findings (2004, for a review see also Rastle & Davis, 2008) who found no statistical difference between the amount of priming obtained for truly suffixed and pseudo-suffixed words. We consider three factors that might provide an explanation for the increased amount of truly suffixed priming in the present experiment.

First, the word items were chosen from a children's printed word database and were therefore of particularly high frequency. High frequency items are activated more readily and processed more thoroughly than low frequency items. Therefore, it is possible that high frequency items would be more affected by different degrees of semantic prime-target relatedness and thus more prone to produce semantic transparency effects. In line with this interpretation, the post-hoc analysis across truly and pseudo-suffixed trials revealed a marginally positive correlation between the amount of priming and logarithmic target frequency. In addition, a target frequency comparison of Rastle et al.'s and our own materials revealed that truly and pseudo-suffixed target word frequency was significantly higher in our study, t = 1.98, p < .001.

Second, the display duration for the masked primes (50 ms) was longer than that used in other adult studies (40 ms; e.g. Rastle et al., 2004). It is well known that, in adults, the degree of semantic influence in masked priming increases substantially at presentation durations of 50+ ms (e.g. Perea & Gotor, 1997; Rastle et al., 2000). Therefore, one possible explanation for the increased priming effect in the truly suffixed condition might be that, since participants were given more time to process the prime more thoroughly, the likelihood of producing semantic-transparency effects was increased.

Third, while the present set of truly suffixed items contained a mixture of derivational affixes (11; e.g. *ly* and *y*), inflectional affixes (14; e.g. *ed* and *ing*) and affixes that are used both derivationally and inflectionally (9; e.g. *er* and *en*), the affixes used in the pseudo-suffixed condition were predominantly derivational (19 derivational, 2 inflectional, 13 derivational-inflectional). Recent evidence (e.g. Crepaldi, Rastle, Coltheart, & Nickels, 2010; Orfanidou, Davis, & Marslen-Wilson, 2010) suggests that there are differences in the representation of inflectional and derivational endings (e.g. in their robustness to orthographic changes). The different proportions of derivational and inflectional affixes across conditions could therefore potentially be responsible for the increased priming of truly suffixed items. However, inconsistent with this interpretation, there was no correlation between amount of priming and type of affixation, which appears to indicate that the greater number of inflectional endings in the truly suffixed condition did not affect the observed pattern of results.

Taken together, the findings presented in Experiment 1 support the hypothesis that a) morphological decomposition operates on the basis of orthographically defined morphemic sub-units, and b) that morphological decomposition in adults is also influenced by semantically defined morphemic representations. These results are consistent with parallel dual-route accounts, according to which morpho-orthographic and morpho-semantic decomposition co-occur via two parallel processing routes (e.g. Baayen et al., 1997; Diependaele et al., 2009; Feldman et al., 2009). They are also consistent with form-then-meaning accounts, which consider that early stages of morpho-orthographic decomposition are followed by a later morpho-semantic processing stage (e.g. Crepaldi et al., 2010; Longtin & Meunier, 2005; Rastle & Davis, 2008; Rastle et al., 2004). They are not consistent with supra-lexical decomposition accounts (Giraudo & Grainger, 2003; Marslen-Wilson et al., 1994), which consider that the decomposition of polymorphemic words is entirely governed by semantic transparency.

Having established that evidence for morpho-orthographic decomposition, supplemented by semantic transparency effects, could be demonstrated in adults with the present set of materials, we moved on to examining the pattern of effects in developing readers.

Experiment 2

The aim of Experiment 2 was to examine whether the masked morphological priming effects obtained in skilled readers could also be found in children who are learning to read, and to investigate what the nature of these priming effects are. As in Experiment 1, facilitation in responding to target stems preceded by truly suffixed, pseudo-suffixed and non-suffixed primes was examined. Year 3 readers (age 8-9) were selected as our lowest age group, as these are the youngest children that can be expected to have sufficiently large sight vocabularies to perform the lexical decision task and that have been demonstrated to show reliable masked priming effects (Castles et al., 2007; Castles et al., 1999). Year 5 children (age 10-11), with two further years of reading experience, were chosen as our highest age group.

As in Experiment 1, the presence of a structurally based morpho-orthographic mechanism in developing readers would be evidenced by significant priming in both the pseudo-suffixed and the truly suffixed conditions. The presence of a purely morpho-semantic mechanism would be evidenced by priming only in the truly suffixed condition. The presence of both morpho-orthographic and morpho-semantic processing would be evidenced by priming in both conditions, but greater facilitation in the truly suffixed condition than in the pseudo-suffixed condition. In none of the two age groups was priming expected to occur in the non-suffixed control condition.

An additional goal of our study was to provide some initial insights into the strategies that children might use to establish form-based morphological representations, which are then later used as the basis for automatic decomposition processes. Rastle and Davis (2008, pp. 953-959) propose three alternative options in this regard, and the present study aimed at providing some adjudication between these alternatives by exploring the pattern of priming effects across age groups and by exploring the relationship between these priming effects and some key psycholinguistic variables.

The first option proposed by Rastle & Davis (2008) is that children initially use form-meaning regularities to process morphological structures and that a more abstract form-based parsing mechanism arises only at a later stage in reading development. On this account, priming of true morphological structures (*teacher-TEACH*) should surface in developing readers first and priming of pseudo-morphological structures (*mother-MOTH*) would only occur at a later stage in reading development. Moreover, priming should increase for increased proportions of semantic prime-target overlap (e.g. the proportion of semantic overlap of *fly* and *flying* is higher than the proportion of semantic overlap of *mood* and *moody*).

The second option is that the formation of structural morphemic subunits involves learning to group strings of highly-frequent letter sequences into subunits. On this account, pseudo-morphological priming (e.g. *mother-MOTH*) and true morphological priming (e.g. *golden-GOLD*) should be evidenced at the same stage in reading development. In addition, affixes would be represented as independent orthographic units because of the frequency of their occurrence, such that more priming should be obtained for primes with high frequency suffixes (e.g. *ing*, which occurs in 6058 words according to the CELEX database) than for primes with low frequency suffixes (e.g. the suffix *en* which occurs in only 547 words).

The third option proposed by Rastle and Davis (2008) is that the acquisition of morphemically-structured orthographic representations is based on the grouping of letter sequences on each side of low-frequency positional probabilities at morpheme boundaries. This hypothesis is based on the idea that bigram and trigram frequencies are typically lower for letters crossing the morpheme boundary than for morpheme-internal letters. For example, the relatively low bigram frequency of *pf* in *helpful* would provide a useful segmentation tool for developing readers to discover letter sequences representing morphemic components in written text. Like the second account, this third account predicts the simultaneous onset of pseudo-morphological priming (e.g. *mother-MOTH*) and true morphological priming (e.g. *golden-GOLD*) in reading development. Moreover, greater priming would be expected to occur for primes with low frequency morpheme boundary bigrams (e.g. *pf* in *helpful*) than for high frequent boundary bigrams (e.g. *ef* in *hopeful*).

To assist in exploring these alternatives, we measured suffix frequency, position specific bigram frequency and the level of semantic relatedness between the stems and targets, as well as target frequency and type of affixation (adapted from Experiment 1). At the participant level, we assessed the children's general morphological knowledge using an oral morphological awareness task and their reading ability using word and nonword reading tasks, to investigate subject-specific factors that might be associated with the development of automatic morphological processing mechanisms in children.

Method

Participants

Forty-two Year 3 children (mean age: 8.1 years) and thirty Year 5 children (mean age: 10.1 years) from a girls school in Sydney participated in the study[4]. We made the decision to test extra Year 3 children since previous lexical decision studies found that a proportion of younger readers needed to be excluded due to performing at chance level in the lexical decision task (e.g. Castles et al., 1999). This turned out not to be the case in the present study. All participants were native English speakers and had normal or corrected-to-normal vision.

[4] Although the study solely tested girls, we had no reason to expect any sex differences in a basic word recognition experiment such as this.

Materials and Procedure

Masked Primed Lexical Decision Task. The same materials and procedure as in Experiment 1 were used.

Reading ability task. The Castles and Coltheart Test 2 (Castles, Coltheart, Larsen, Jones, Saunders, & McArthur, 2009) was administered to assess the children's ability to sound out words and their whole word recognition ability. Year 3 and Year 5 children were asked to read out aloud 40 regular words (e.g. *cat*), 40 irregular words (e.g. *yacht*) and 40 nonwords (e.g. *gop*), which were presented one at the time, in mixed order. The degree of difficulty gradually increased throughout the task.

Morphological awareness task. A modified version of the sentence completion task by Carlisle (1988) was used to examine the children's ability to choose appropriate derivational forms in an oral sentence context (Carlisle, 2000; Roman et al., 2009). The test contained 20 stem words and 20 sentences with a missing word at the end of the sentence. The experimenter would first read a word and then the corresponding sentence (e.g. '*Perform. Tonight is the last* __.'). Children were then asked to fill the gap with a corresponding correct morphological form of the word presented at the beginning of the task (*performance*). Half of trials required the selection of a matching morphologically derived word form (see example above) and half involved the production of corresponding stem morphemes (e.g. '*Discussion. The friends have a lot to* __.' [*discuss*]).

Results

Masked primed lexical decision task

Response latencies for incorrect responses for the primed lexical decision task were collected and removed (12.3% of the data in Year 3 and 5.3% in Year 5). No subjects were discarded as all error rates were below 40%. Furthermore, different trimming procedures were tried (e.g. Standard Deviation Trimming and Absolute-Value Trimming), but they did not significantly change the size or direction of the main effects and interactions. The main analyses were performed using linear mixed-effects modeling analysis following the procedures used in Experiment 1. A model was fitted with eight fixed effects factors (Trial Number, Prime Type: Related vs. Unrelated, Item Type: Truly Suffixed vs. Pseudo-suffixed vs. Non-suffixed, Age Level: Year 3 vs. Year 5, the interaction between Prime Type and Item Type, the interaction between Prime Type and Age Level, the interaction of Item Type and Age Level, and the interaction between Prime Type, Item Type and Age Level) and two random-effects factors (random intercepts for Subjects and Items). The linear mixed-effects model estimated pair-wise level-by-level analyses for fixed-effects factor analyses yielding three Item Type by Prime Type by Age Level comparisons. The response latency analysis revealed that the three-way interaction of Prime Type, Item Type and Age Level (i) was significant across truly suffixed and non-suffixed trials, t = 1.95, p = .05, was (ii) non-significant across pseudo-suffixed and non-suffixed trials, t = 1.67, p = .10, and was (iii) non-significant across truly suffixed and pseudo-suffixed trials, t = 0.25, p < .80[5]. There were no significant interactions in the error data. The mean reading latencies and error rates for the Year 3 and Year 5 participants are presented in Table 3.

To further unpack the significant three-way interaction of Item Type, Prime Type and Age Level, separate generalised linear mixed-effects models were fitted for each Age Group (Year 3 and Year 5) and each Item Type (Truly Suffixed, Pseudo-suffixed and Non-suffixed), with two fixed effects factors (Trial Number; Prime Type: Related vs. Unrelated) and two random-effects factors (random intercepts for Subjects and Items).

The linear mixed effect modeling analysis on response latencies in Year 3 revealed that targets preceded by truly suffixed primes (*golden-GOLD*) were responded to significantly faster than their unrelated controls (*frosty-GOLD*), t = 2.32, p = .02. However, no priming was observed in the Pseudo-suffixed (*mother-MOTH* vs. *greedy-MOTH*), t = 0.15, p = .88, or Non-suffixed (*spinach-SPIN* vs. *magical-SPIN*) conditions, t = 1.18, p = .24. No other effects were significant. The effects in the error data were not significant. Similarly, the response latency analysis of Year 5 revealed that priming was significant in the Truly Suffixed condition, t = 2.86, p = .004. As with the Year 3 children, no priming was observed in the Pseudo-suffixed condition, t = 0.53, p = .60. In the Non-suffixed condition, a significant inhibitory priming effect was found, t = 2.96, p = .003. No other effects were significant and the effects in the error data were also not significant.

[5] To confirm the present results, we performed ANOVAs of the latency data, by subject and by item, with the three factors Item Type (Truly Suffixed vs. Pseudo-suffixed vs. Non-suffixed), Prime Type (Related vs. Unrelated) and Age Group (Year 3 vs. Year 5). The analysis revealed a significant main effect of Item Type, $F_1(2, 69) = 6.1$, p = .002, and $F_2(2, 32) = 8.37$, p < .001, and an interaction of Item Type with Prime Type which was significant in the subject data, $F_1(2, 69) = 4.18$, p = .019, and approached significance in the item data, $F_2(2, 32)$ = 2.66, p = .086. Moreover, there was a significant main effect of Age Group, $F_1(2, 70) = 22.88$, p < .001.

Table 3. *Mean reaction times and error rates averaged across Year 3 and Year 5 participants. Standard deviations are shown in parentheses.*

	Year 3		**Year 5**		
Condition	Reaction times	Error Rates	Reaction times	Error Rates	Example
		Truly suffixed			
related	1035 (246)	9.9 (9.8)	796 (151)	2.5 (5.0)	*golden-GOLD*
unrelated	1107 (270)	10.1 (9.9)	841 (149)	3.0 (4.5)	*frosty-GOLD*
priming effect	72	0.2	45	0.5	
		Pseudo-suffixed			
related	1122 (331)	15.3 (10.5)	887 (234)	8.5 (7.2)	*mother-MOTH*
unrelated	1115 (283)	17.8 (12.2)	864 (160)	6.8 (6.1)	*greedy-MOTH*
priming effect	-7	2.5	-23	-1.7	
		Non-suffixed			
related	1109 (310)	10.2 (8.1)	912 (192)	6.1 (5.8)	*spinach-SPIN*
unrelated	1142 (320)	10.6 (11.3)	842 (152)	4.8 (4.7)	*magical-SPIN*
priming effect	33	0.4	-70	-0.7	

Finally, to compare the magnitude of truly suffixed priming in Year 3 and Year 5 readers, we performed a mixed-effects analysis across both age groups using four fixed effects factors (Trial Number; Prime Type: Related vs. Unrelated, Age Group: Year 3 vs. Year 5, and the interaction of Prime Type and Age Group) and two random-effects factors (random intercepts for Subjects and Items). The analysis revealed a significant main effect of Prime Type, t = 2.62, p = .01 and a significant main effect of Age Group, t = 5.07, p < .001. The interaction of Prime Type and Age Group was not significant, t = 0.02, p = .98, indicating that the magnitude of Truly suffixed priming did not differ across the two age groups.

Relationship between priming and reading ability and morphological awareness

Summary statistics for accuracy in reading the Castles and Coltheart 2 regular words, irregular words and nonwords, and the morphological awareness scores, for the Year 3 and Year 5 readers, are presented in Table 4.

Table 4. *Summary of Reading Ability Scores and Morphological Awareness Scores for Year 3 and Year 5 readers.*

Task	Year 3	Year 5
Regular word reading (/40)		
Mean (SD)	33.2 (5.2)	37.3 (2.6)
Range	19-40	30-40
Irregular word reading (/40)		
Mean (SD)	19.9 (4.2)	24.9 (3.8)
Range	9-31	13-32
Nonword reading (/40)		
Mean (SD)	27.9 (8.9)	33.8 (5.4)
Range	8-40	14-40
Morphological awareness (/20)		
Mean (SD)	11.7 (2.7)	15.9 (1.4)
Range	5-16	14-19

In order to examine the relationship between these scores and the magnitude of priming in the three morphological priming conditions, we collapsed the results across the Year 3 and Year 5 readers and performed a correlation analysis. The results are presented in Table 5.

Table 5. *Pearson r correlations between magnitude of priming and reading ability and morphological awareness scores, collapsed across Year 3 and Year 5 readers.*

Task	Truly suffixed priming	Pseudo-suffixed priming	Non-suffixed priming
Regular word reading	.273*	.141	.207
Irregular word reading	.147	.010	.158
Nonword reading	.226[a]	.178	.196
Morphological awareness	.219[b]	.038	.140

* $p < .05$
[a] approaching significance, $p = .056$
[b] approaching significance, $p = .064$

In the Truly Suffixed condition there was a significant positive correlation between magnitude of priming and regular word reading accuracy, and a marginally significant positive correlation between magnitude of priming and nonword reading accuracy and morphological awareness. Due to the lack of significant priming in the Pseudo-suffixed condition, we did not expect to find evidence for a relationship between priming and reading ability or morphological awareness scores in this condition, and the results confirmed this. Similarly, there were no significant correlations in the Non-suffixed condition.

Relationship between priming and item characteristics

To explore whether the magnitude of priming obtained across Year 3 and Year 5 data were influenced by item-specific characteristics such as target frequency, type of affixation, suffix frequency, boundary bigram frequency, or semantic prime-target relationships, we performed post-hoc analyses across item means. First, we collapsed across truly suffixed and pseudo-suffixed trials, to establish whether there was an overall relationship between priming and target frequency, type of affixation, suffix frequency or position specific boundary bigram frequency. In addition, we examined the influence of the proportion of semantic prime-target overlap on priming. This analysis was carried out exclusively within the truly suffixed condition, so as to avoid a confound with the pseudo-morphological manipulation (where, by definition, the semantic overlap was lower). Target frequency, suffix frequency and position specific boundary bigram frequency were both extracted from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993), whereas the proportion of semantic prime-target overlap was calculated on basis of the Latent Semantic Analysis Web facility (http://lsa.colorado.edu). The results are presented in Table 6.

Table 6. *Summary of the Pearson r correlation analysis of priming with Target Frequency, Type of Affixation, Suffix Frequency, Position Specific Boundary Bigram Frequency and Semantic Prime-Target Overlap, collapsed across Year 3 and Year 5 readers.*

Feature	
	Truly and Pseudo-suffixed priming
Target Frequency	.314**
Type of Affixation	.056
Suffix Frequency	.329**
Position Specific Boundary Bigram Frequency	.073
	Truly suffixed priming
Semantic Prime-Target Overlap	.402*

* $p < .05$
** $p < .01$

There was a significant positive correlation between magnitude of truly and pseudo-suffixed priming and target frequency and between magnitude of truly and pseudo-suffixed priming and suffix frequency. However, the correlation of magnitude of truly and pseudo-suffixed priming with type of affixation or position specific boundary bigram frequency was not significant. Moreover, the results revealed a significant positive correlation of magnitude of truly suffixed priming with proportion of semantic prime-target overlap.

Discussion

Experiment 2 revealed that both Year 3 and Year 5 readers produced significant priming in the truly suffixed condition (*golden-GOLD* vs. *frosty-GOLD*), but not in the pseudo-suffixed (*mother-MOTH* vs. *greedy-MOTH*) or non-suffixed condition (*spinach-SPIN* vs. *magical-SPIN*).

The lack of priming in the non-suffixed control condition (*spinach-SPIN*) indicates that the pure orthographic relationship between prime and target was not sufficient to produce priming in this experimental context for both groups of developing readers. Moreover, the Year 5 readers actually showed a significant effect of inhibition, an effect that has previously been observed (see also Grainger, Colé, & Segui, 1991; Longtin et al., 2003; Rastle et al., 2000). This reinforces the argument that the observed facilitation in the truly suffixed condition in all three groups is likely to be due to the influences of morphological factors, and not related to orthographic prime-target overlap.

Critically, both Year 3 and Year 5 children showed significant priming in the truly suffixed condition. However, neither Year 3 nor Year 5 readers produced priming in the pseudo-suffixed condition. This differs from earlier findings obtained with adults showing significant pseudo-morphological priming and has important implications for our understanding on how developing readers begin to develop morphological parsing mechanisms (see General Discussion). With respect to the youngest age group of Year 3 readers, the lack of priming in the pseudo-suffixed condition is perhaps not surprising, suggesting that, due to their relatively inexperienced stage in reading development, these children had not yet established the abstract structural morphological representations that might trigger an automatic decomposition process. However, the results for the Year 5 readers were more surprising, and reveal that even at this notably more advanced stage in reading development, automatic form-based decomposition does not appear to occur. Hence, the present research suggests that form-based morphological decomposition is quite a late-occurring milestone in reading acquisition.

Due to the lack of priming in the pseudo-suffixed and non-suffixed conditions in Year 3 and Year 5 readers, the truly suffixed priming effect can only be explained in terms of higher-level linguistic factors. However, it cannot be determined from the present study exactly what these factors might be, and whether the effect is entirely attributable to the semantic relationship between the prime and target or due to a morphological decomposition mechanism that is only applied to words with a genuine morphological structure. Further research is needed to distinguish between these two alternatives, but in our view it is unlikely that the observed effects are entirely semantically-based, for the following reasons.

First, there was a marginally significant correlation between the magnitude of truly and pseudo-suffixed priming and the children's performance on the morphological awareness task: children who showed more evidence of knowledge of morphological substructures in their oral language showed a tendency to benefit more from the genuinely suffixed prime. This would seem to suggest some genuinely morphological locus to the effects observed. Second, the analysis across truly and pseudo-suffixed items revealed a significant correlation between the magnitude of priming and suffix frequency, with increased priming for more frequent suffixes; again this would seem to point to a morphological influence on the priming. Finally, at least in adults, masked priming of lexical decisions appears to be relatively insensitive to semantic factors (Longtin & Meunier, 2005; Meunier & Longtin, 2007; Rastle et al., 2004). Therefore, although influences of semantics on masked morphological priming have been reported (e.g. Feldman et al., 2009), it seems unlikely that the present priming effects were uniquely driven by the semantic relationship between the prime and the target, without any contribution from morphological factors.

Not surprisingly, in line with the adult data of Experiment 1, it was found that children produced more priming for high frequency target words than for low frequency target words, but there was no relationship between magnitude of priming and type of affixation. Most critically, however, the present Year 3 and Year 5 data provide additional insights with respect to Rastle and

Davis' (2008) three proposed morphological acquisition strategies. No relationship was found between the magnitude of truly and pseudo-suffixed priming and morpheme boundary bigram frequency, suggesting that this factor was not modulating morphological processing at this level. However, more priming was obtained for prime-target pairs sharing a high proportion of semantic overlap (e.g. *flying-FLY*) than for those with a low proportion of semantic overlap (e.g. *moody-MOOD*), which is consistent with the hypothesis that children use form-meaning regularities to acquire morphological knowledge. This is also consistent with the finding of priming in the truly suffixed (*teacher-TEACH*) but not in the pseudo-suffixed condition (*mother-MOTH*). Moreover, in line with Rastle & Davis' (2008) second hypothesis, our analysis showed that, as suffix frequency increases, priming in the truly and pseudo-suffixed condition increases as well. Critically, being purely frequency based, this acquisition strategy also predicts that the onset of pseudo-morphological priming (e.g. *mother-MOTH*) and true morphological priming (e.g. *farmer-farm*) should surface at the same stage in reading development. The present data shows that this is not the case, suggesting that this cannot be a full account.

The results of the present study thus appear to support the hypothesis that the acquisition of abstract morphemic representations in young readers is at least partially based on (i) building clusters of form-meaning regularities and (ii) grouping strings of high-frequency letter sequences into subunits. No evidence for the grouping of low-frequency bigrams at morpheme boundaries was found. It can thus be ruled out that children uniquely relied on learning letter probabilities, such as suffix and morpheme-boundary bigram frequencies. If the developing morphological parsing system solely relied on orthographic probabilities, truly and pseudo-suffixed priming should have emerged at the same time. Our data instead suggest that children first learn to recognize morphologically related full forms (e.g. *teacher*, *teaching*, etc.) and that only after the acquisition of a number of whole words do children reach a more abstract level of understanding of morphological structures by linking the meanings of related entities within the words (e.g. *teach* + *er* = someone who teaches). Such a morphological parsing system would then continuously grow with further exposure to form-meaning regularities (e.g. *teach-er*, *farm-er*, *mix-er*, etc.), as well as high-frequency letter strings (e.g. *er*, *ing*, etc.), to eventually result in a form-based parsing mechanism applied to every letter string with the mere appearance of morphological complexity (e.g. *moth-er*, *corn-er*, *numb-er*, etc.).

Although no evidence for boundary bigram frequency effects was found, it cannot be ruled out that learning low probability bigrams (e.g. *pf*, *tm*, etc.) contribute to the formation of the morpho-orthographic parsing system at a later stage of reading acquisition than was examined here and it cannot be established when exactly in reading acquisition children such a benefit might begin to occur. Further research is needed to systematically investigate the role of letter probabilities in the development of morphological processes in visual word recognition over the full range of reading ability.

General Discussion

In the present experiments, Year 3 and Year 5 readers showed significant priming of the latency of their lexical decisions when stem word targets were preceded by truly suffixed primes (*golden-GOLD* vs. *frosty-GOLD*), but not when they were preceded by pseudo-suffixed primes (*mother-MOTH* vs. *greedy-MOTH*). In contrast, the adult participants displayed significant facilitation from both truly suffixed and pseudo-suffixed primes, although the priming effect was stronger in the truly suffixed condition. No priming was observed for any group in the non-suffixed condition (*spinach-SPIN* vs. *magical-SPIN*).

Extending a finding that has earlier been obtained with adults (Rastle et al, 2004), Year 3 and Year 5 children's recognition of a stem target was found to be facilitated by the prior presentation of a morphologically related prime (*golden-GOLD*). However, in contrast to the effects previously shown with adults and also observed in the adult group here, the developing readers did not display any sign of priming in the pseudo-morphological condition (*mother-MOTH*). This suggests that, while an automatic non-strategic and semantically-blind morphological decomposition process appears to occur in skilled adult readers, such that a semantic relationship between the stem and the affix is not necessarily required to trigger the decomposition into morphemic subunits (Longtin & Meunier, 2005; Rastle et al., 2004), such form-based morphological decomposition does not occur in developing readers even as advanced as Year 5.

In line with previous results from the adult literature, Experiment 1 showed that morphological processing in visual word recognition in skilled readers is constrained by two key mechanisms: morpho-orthographic decomposition, based on the segmentation into orthographically defined morphemic units, and morpho-semantic decomposition, based on the segmentation into semantically defined morphemic units. Two classes of theories have been proposed that can account for both types of mechanisms: form-then-meaning accounts and parallel dual-route accounts.

Form-then-meaning accounts consider that morphological decomposition is always initially based on morpho-orthographic processing mechanisms, which decomposes any letter string with the mere appearance of morphological complexity, whereas morpho-semantic mechanisms require more processing time and are only true for semantically transparent morphological structures (e.g. Crepaldi et al., 2010; Rastle & Davis, 2008; Taft, 2003). Such accounts predict that early automatic morphological processing is semantically blind, which we evidenced in the context of masked priming (for converging evidence, see also McCormick, Rastle, & Davis, 2007; 2009; Rastle et al., 2004; Rastle & Davis, 2008). Semantic-transparency effects, however, should only begin to emerge at higher-level morpho-semantic processing stages. The present masked priming results confirm this prediction, given that participants were highly familiar with the present set of high frequency word materials while prime durations were relatively long, allowing more thorough stimulus processing.

Parallel dual-route accounts, on the other hand, propose two parallel processing routes, such that every input letter string is simultaneously mapped onto both morpho-orthographic and morpho-semantic representations (e.g. Diependaele et al., 2009; see also Baayen et al., 1997; Feldman et al, 2009). Consistent with our present findings, this account postulates that morpho-orthographic and morpho-semantic priming effects should both be found with sufficiently short prime presentation durations. It has further been suggested that, while morpho-orthographic priming should gradually disappear with increased prime durations, morpho-semantic priming effects should remain robust (see Diependaele et al., 2009). This may perhaps provide an explanation for the striking difference between truly and pseudo-suffixed priming effects observed in the adult data. Bearing in mind the high frequency and long presentation durations of our present word materials, it is possible that there was enough time for morpho-semantic representations to gradually become stronger, whilst morpho-orthographic activations were already beginning to fade away.

Both classes of theory present frameworks of morphological processing in skilled readers, but do not make predictions about the acquisition of morphological knowledge in visual word recognition. One interpretation of the present pattern of findings is that, in the process of acquiring a visual word recognition system, children learn morphologically complex full forms first, and only develop affix-representations at some later stage. This would involve the mapping of letter units (e.g. *g-o-l-d-e-n)* onto an orthographic lexicon, which would in turn be mapped onto corresponding semantic representation. Once the acquisition of a morphologically complex full form (e.g. *golden*) has been accomplished, children may learn to identify affixes as being part of these morphologically complex structures (*gold* + *en*). Only after children have established semantically defined morphemic units, these may begin to send feedback to an orthographic lexicon and an affix-storage will gradually form. It cannot be established from the present results whether or not the acquisition of a purely structural form of morphological parsing is uniquely based on learning form-meaning regularities and grouping high-frequent letter sequences, or if learning low-frequent letter probabilities is also beneficial. Critically however, children will begin to automatize morphological segmentations and to identify morpho-orthographic sub-structures only *after* the acquisition of a morpho-semantic parsing system.

Full forms may initially be acquired but it is possible that they are later recoded as decomposed entries, and that access to the whole-word is subsequently only achieved on basis of its morphemic subunits. This is in line with form-then-meaning accounts suggesting that any morphologically complex letter string is always initially decomposed (e.g. Rastle & Davis, 2008; Taft, 2003). Alternatively, it could be that the representations of morphologically complex full forms remain available in a direct access route and that additional decomposed entries are added. This would result in a reading network in which the representations of whole-words and morphemes are simultaneously available, such as is proposed in parallel dual-route accounts of morphological processing (Baayen et al., 1997; Diependaele et al., 2009). For future research, it would be interesting to further explore the exact strategies that children use to establish form-based morphological representations, to distinguish between these alternatives.

In conclusion, the present masked priming study demonstrates that Year 3 and Year 5 children are sensitive to the presence of morphologically complex words during the process of visual word recognition. However, in contrast to the typical pattern obtained in adults, no evidence was found for an automatic, semantically-blind morphological parsing mechanism in these developing readers. Future research should focus on examining children at a more advanced stage than Year 5, so as to determine the youngest age at which form-based morphological decomposition becomes evident.

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Appendix 1

The stimuli used in Experiment 1 and 2 are presented below. Targets are listed in uppercase, immediately followed by its corresponding related prime and then followed by its unrelated prime, both in lowercase.

Truly suffixed condition: *WALK, walked, smelly; FILL, filled, lovely; TOAST, toaster, grocery; GOLD, golden, frosty; CRY, crying, posted; BAD, badly, liked; DRY, drying, weaker; OPEN, opened, boards; SHY, shyly, mower; FLY, flying, softer; PLAY, playing, tighter; MIX, mixer, doing; BUY, buying, louder; FIX, fixing, boiler; TEACH, teacher, robbery; ACT, acting, nearer; MOOD, moody, waved; MAIN, mainly, fuller; FARM, farmer, stormy; LUCK, lucky, named; BOX, boxer, messy; HARD, harder, filthy; TRY, trying, soften; EAT, eating, locker; SLY, slyly, fixed; LAY, layer, milky; BUSH, bushy, moved; CREAM, creamy, darker; SLOW, slowly, leader; DEEP, deeply, banker; AIM, aimed, rainy; SAD, sadly, loved; SEW, sewed, windy; DIRT, dirty, stars.*

Pseudo-suffixed condition: *MISS, mission, longest; SLIM, slimy, eater; EAST, easter, likely; LAD, lady, eggs; SHOULD, shoulder, fighting; CORN, corner, sticky; OFF, offer, dolly; SHOW, shower, fallen; SCAR, scary, older; MAST, master, grassy; FOR, forest, prayer; POST, poster, bricks; DRAW, drawer, postal; MOTH, mother, greedy; FLOW, flower, saving; PART, party, tower; LIST, listen, sleepy; MAN, many, used; MET, metal, sandy; ARM, army, cats; NAUGHT, naughty, painter; BELL, belly, eaten; FAST, fasten, nearly; FAIR, fairy, beans; BOTH, bother, widely; NUMB, number, fluffy; MILL, million, clearly; EVER, every, lower; BUS, busy, aged; FACT, factory, cheaper; SAND, sandal, wooden; COUNT, country, filling; HUNG, hungry, warmer; FIN, finish, caller.*

Non-suffixed condition: *ADD, address, speaker; FREE, freeze, tender; SING, single, curled; AGAIN, against, tidying; THIN, think, early; TEA, tease, salty; WIND, window, fruity; HOW, howl, ants; CAR, carrot, sooner; BEE, beer, maps; TWIN, twinkle, lighter; SIGH, sight, curly; HOT, hotel, risky; WIN, wink, legs; CART, carton, player; ARE, area, cars; CHIN, china, jelly; TOO, tooth, bumpy; BEG, begin, snowy; SKI, skirt, dusty; SPIN, spinach, magical; MEN, menu, bags; CROW, crown, going; TURN, turnip, slower; YELL, yellow, hunter; STAR, starve, camped; SHOVE, shovel, lately; COME, comet, cried; WON, wonder, gloomy; PAST, pasta, rocky; DRAG, dragon, poetry; PILL, pillow, lesser; CAME, camel, bossy; LESS, lesson, richer.*

Summary and conclusions

Summary and conclusions

This thesis has investigated the role of morphological analysis during reading in both children and adults. The main goal of the thesis was to extend previous research investigating morpho-orthographic and morpho-semantic decomposition mechanisms in children and adults, particularly focusing on (i) studying the type of orthographic information that allows readers to recognize orthographic similarity across different morphologically related words (Chapters 2-4), and (ii) examining how orthographic representations become morphemically structured in the first place (Chapter 5). This research has focused on early unconscious morphological processing stages, and specifically examined how lower-level orthographic and higher-level semantic influences affect morphological decomposition. In order to explore early non-strategic processing stages, Chapters 2-5 drew upon the masked primed lexical decision paradigm, and Chapters 2-4 used masked transposed-letter priming paradigm in particular.

Chapter 1 provided a general overview of current morphological processing and letter position encoding accounts, highlighting the interplay of morpho-orthographic and morpho-semantic processing in visual word recognition, as well as the interplay between letter position coding and morphological analysis. Chapter 2 explored differences between within-boundary letter transpositions (*d**ra**kness*) and across-boundary letter transpositions (*dar**nk**ess*) in skilled readers, using unprimed and masked primed lexical decision. Significant transposed-letter similarity effects were found that were independent of the morphological position of the letter transposition, which suggests that, in English, morphologically complex whole-word representations can be directly accessed at initial stages in visual word recognition. In order to more specifically examine how morphemes are positionally defined, this research was extended to the context of affixed transposed-letter nonword primes (*w**ra**nish*), in English (Chapter 3) and Spanish (Chapter 4). Chapter 3 showed that stem-target recognition is significantly facilitated by the prior masked presentation of a suffixed TL-nonwords (*wranish-WARN*), but not when targets are preceded by non-suffixed TL-nonwords (*wranel-WARN*), suggesting that affix-stripping is triggered by a mechanism operating at very early orthographic processing stages while letter-position coding is not yet fully resolved, showing that morphemic structure and letter-position are encoded at the same stage, prior to lexical access. Chapter 4 compared (i) suffixed word primes (*doloroso-DOLOR* [*painful-PAIN*]) to their transposed-letter counterparts (e.g. *d**lo**oroso-DOLOR*), and (ii) suffixed nonword primes (*totalito-TOTAL* [*a little total*]) to their transposed-letter counterparts (e.g. *t**to**alito-TOTAL*). The two word-prime conditions (*doloroso-DOLOR* vs. *d**lo**oroso-DOLOR*) produced equivalent priming effects, whereas priming was significantly reduced in the related nonword condition (*totalito-TOTAL*) and was absent in the transposed-letter nonword condition (*t**to**alito-TOTAL*), suggesting that early morpho-orthographic parsing mechanisms benefit from semantic constraints.

Finally, Chapter 5 examined masked morphological priming in two groups of developing readers (Year 3 and Year 5), comparing truly suffixed (*golden-GOLD*), pseudo-suffixed (*mother-MOTH*), and non-suffixed (*cashew-CASH*) prime-target pairs. In both Year 3 and Year 5 readers, priming only occurred when the prime and the target shared a true morphological relationship, and not when the relationship was pseudo-morphological, indicating that Year 3 and Year 5 children have not yet automatized morpho-orthographic decomposition mechanisms. It was further shown that factors such as suffix frequency and semantic prime-target overlap positively influence children's ability to decompose morphologically complex words, which thus provides some initial insights into the type of information that children use to acquire morphological knowledge. Taken together, the findings presented in this thesis have important implications for current morphological processing accounts, as well as letter position encoding theories, which we discuss below.

Morpho-orthographic decomposition during reading

One of the goals of this thesis was to examine whether morpho-orthographic segmentation occurs even when no meaning is associated with the whole letter string. Therefore, we extended our investigations to the wider context of affixed nonwords and affixed transposed-letter nonwords. Throughout this thesis, we have repeatedly reported evidence for a morpho-orthographic parsing mechanism that "blindly" decomposes any morphologically structured letter string, independently of the syntactic or semantic relationship between the lexical representations of the whole-word and the stem. Masked morphological stem-target priming was not only obtained with truly suffixed (*darker*), pseudo-suffixed (*mother*), and transposed-letter nonword primes (*w**la**ker*), but also with suffixed nonword primes (*walkish*) and suffixed transposed-letter nonword primes (*w**la**kish*). These results demonstrate that early morphological decomposition not only occurs for morphologically structured real words, but also occurs when the prime is a nonword.

Our results challenge full listing theories (Butterworth, 1983; Manelis & Tharp, 1977) and supra-lexical morphological decomposition theories (Giraudo & Grainger, 2001; Giraudo & Grainger, 2003), which consider full forms as direct access units to the lexicon, implying that nonwords would be rejected by the word recognition system prior to decomposition. Our findings, however, do not rule out parallel dual-route models (e.g. Baayen, Burani, & Schreuder, 1997; Baayen, Dijkstra, & Schreuder, 1997; Bertram, Laine, & Karvinen, 1999; Caramazza, Laudanna, & Romani, 1988) that propose that morphologically complex words are simultaneously processed via a decompositional route and a full form route. Parallel dual-route models would thus predict that morphologically complex nonwords can only be accessed via the decompositional route, because of the absence of lexical representations.

In line with previous research (Longtin, Segui, & Hallé, 2003; Rastle & Davis, 2008; Rastle, Davis, & New, 2004), the evidence presented in this thesis confirms that morphologically structured letter strings are analysed and decomposed during reading on basis of orthographic analysis (see Figure 1).

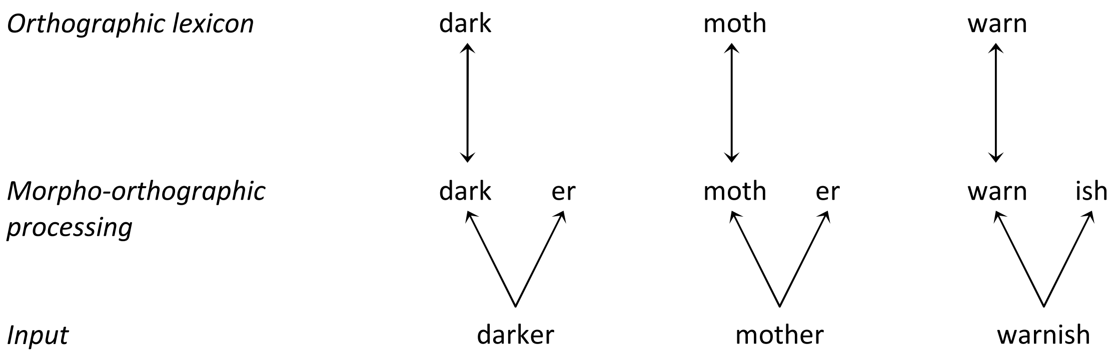

Figure 1: Morpho-orthographic decomposition of morphologically structured letter strings during reading.

Figure 1 represents a model in which morphologically structured words (e.g. *darker*) are automatically decomposed into morpho-orthographic subunits (stem: *dark*, suffix: *er*), guided by an automatic affix detection mechanism (as first proposed by Taft & Forster, 1975). The proposal is that, as affixes are highly frequent and productive, they form strong activation patterns in the visual word recognition system operating over orthographic encoding mechanisms at very early pre-lexical stages of visual word recognition. Such a mechanism would start a search through a letter string, prioritizing letter positions at the beginning and at the end of the letter string, and automatically match affix representations with the input letter string, allowing the automatic detection and stripping of affixes. A letter chunk that successfully matches the representation of an affix is rapidly identified while the word recognition system continues searching for deeper lexical structures throughout the rest of the letter string. Affix representations can thus be thought of as a strongly memorized list of highly frequent and productive morphological subunits which is accessible at very early stages of visual word processing.

Representations of whole-words and morphemes in the orthographic lexicon

A second goal of this thesis was to investigate whether or not morphologically complex words can be directly accessed as whole units at initial word recognition stages. This research question was addressed in Chapter 2, which investigated whether the recognition of whole-word targets can still be achieved when the morphemic parsing route has been distorted by means of across-boundary letter transpositions (e.g. *dar**nk**ess*, *cor**en**r*, etc.). The results revealed that truly suffixed, pseudo-suffixed and non-suffixed TL-nonword primes equally produced priming to their whole-word targets, independently of whether they compared within-morpheme boundary (*d**ra**kness, c**ro**ner, c**sa**hew*, etc.) or across-morpheme boundary transpositions (*dar**nk**ess, cor**en**r, case**eh**w*, etc.), showing that transposed-letter priming effects do not decrease for across-boundary transpositions in English suffixed words. These findings thus show that morphologically complex words can be directly retrieved as full forms from the orthographic lexicon, from which it follows that the recognition of morphologically complex words does not exclusively rely on morpho-orthographic processing (see Figure 2).

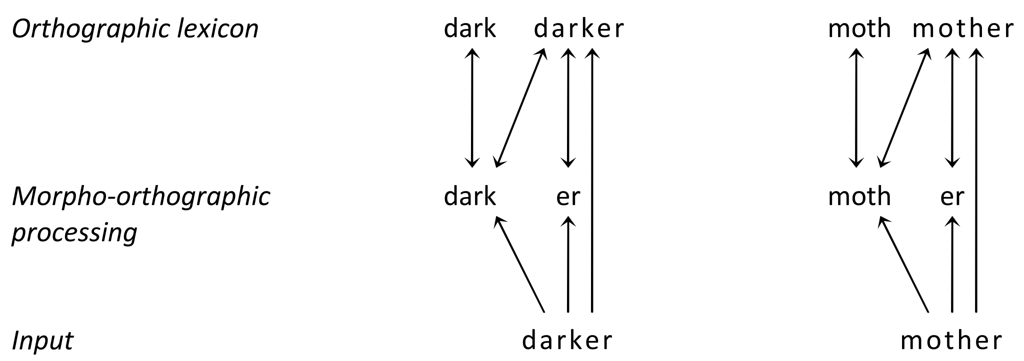

Figure 2: Morphological units of the orthographic lexicon.

Figure 2 extends the model presented in Figure 1, describing the processing path for any given input stimulus to the orthographic lexicon. While any input letter string is always initially mapped onto its corresponding whole-word representation in the orthographic lexicon, it is also simultaneously analysed on the basis of its orthographic form and decomposed into its morpho-orthographic subunits. The form units connect and receive feedback through the orthographic lexicon which comprises representations for any existing letter string, including both monomorphemic units as well as morphologically complex forms (inflectional and derivational).

Semantic influences on early stages of morphological processing

A third key research question of the present thesis was to investigate at what stage in morphological processing semantic influences begin to play a role. Evidence from early masked morphological priming suggests that orthographic information is an important trigger for morphological decomposition in early visual word recognition (Chapter 2-4). But is morphological segmentation uniquely driven by the analysis of orthographic structure or is it also affected by other higher representational levels? To address the role of semantics during morphological processing, we compared words in which the meaning of the whole-word can be derived from the meaning of its morphemic sub-constituents (*walker-WALK*), to words in which there is no semantic relationship between the stem and the whole-word (*mother-MOTH*, Chapter 2 & 5).

Chapter 2 of this thesis (Experiment 3) revealed equal magnitudes of truly suffixed (*walker-WALK*) and pseudo-suffixed priming (*mother-MOTH*). Our results are consistent with those of Rastle et al. (2004; see also McCormick, Rastle & Davis, 2009; Meunier & Longtin, 2007) in showing that there is at least one mechanism which blindly decomposes any letter string purely on basis of morpho-orthographic analysis. These findings rule out that morphological decomposition is a solely semantically driven process, as no priming would be expected to occur in the pseudo-suffixed condition. However, these findings *do not* demonstrate that morpho-orthographic parsing mechanism is the only form of morphological decomposition that occurs.

In Chapter 5 (Experiment 2), a similar experimental design was used, based on a different, more frequent set of truly suffixed and pseudo-suffixed prime-target pairs. Moreover, as opposed to the 40 ms prime durations used in Chapter 2, primes were presented for an extra 10 ms. Similarly to Chapter 2, the results revealed significant priming from both truly suffixed (*golden-GOLD* vs. *frosty-GOLD*) and pseudo-suffixed primes (*mother-MOTH* vs. *greedy-MOTH*), suggesting that morphological decomposition operates on the basis of morpho-orthographic sub-units. In addition, however, the magnitude of truly suffixed priming was significantly greater than the magnitude of pseudo-suffixed priming, which provides evidence for semantically guided parsing into morphemes (for converging evidence, see also Diependaele, Sandra, & Grainger, 2009; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Meunier & Longtin, 2007).

The research presented in Chapter 5 indicates that semantic influences on morphological decomposition can be obtained when more thorough stimulus processing is permitted, due to (i) high familiarity with primes and targets (ii) relatively long prime durations. This suggests that there are two key underlying mechanisms operating over early morphological processing stages during visual word recognition. The first mechanism decomposes any letter string comprising a morphological surface structure (*mother*) into orthographically defined morphemic units, whereas the second mechanism decomposes true morphological structures (*walker*) into semantically defined morphemic units.

Further evidence revealing effects of semantic transparency stems from the Spanish findings presented in Chapter 4, where semantically transparent prime-target pairs (*doloroso-DOLOR* [*painful-PAIN*]) yielded significantly greater priming effects than morphologically structured nonword primes, in which the combination of stem and affix resulted in an entirely meaningless letter string (*totalito-TOTAL* [‘*a little total*’-*TOTAL*). In line with the evidence presented in Chapter 5, these data demonstrate that morpho-orthographic priming effects are supplemented by semantic transparency effects.

These findings are consistent morphological processing accounts which consider that morphological analysis relies on the complex interplay of morpho-orthographic and morpho-semantic representations (e.g. Baayen, Dijkstra et al., 1997; Diependaele et al., 2009). To accommodate the proposal made by such parallel dual-route accounts, we extend the model presented in Figure 2 by incorporating a post-lexical level of morpho-semantic analysis (see Figure 3).

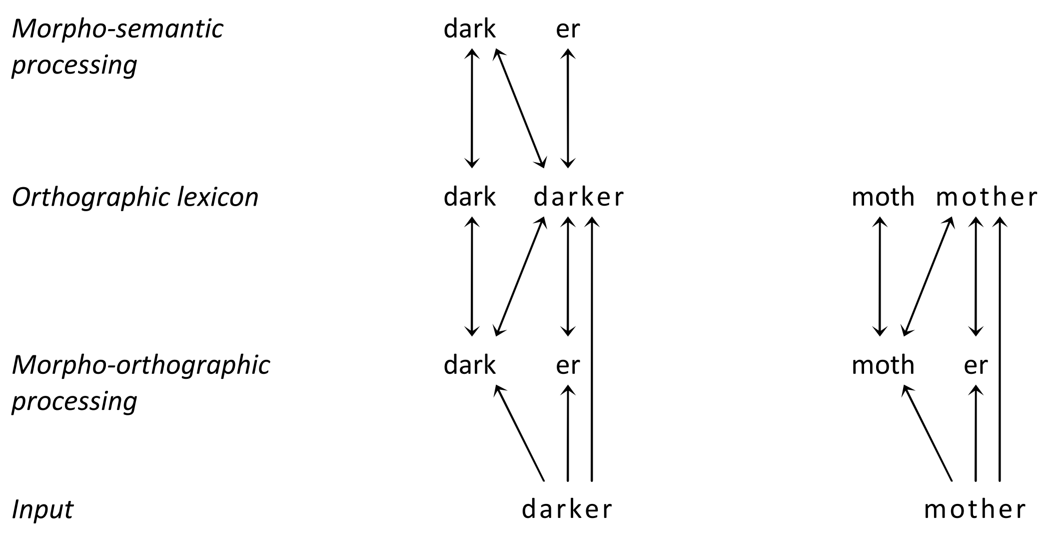

Figure 3: A parallel dual-route model of morpho-orthographic and morpho-semantic processing during visual word recognition.

Figure 3 provides an extension of the model presented in Figure 2. The activation of orthographic representations of morphemes and whole-words is achieved via two parallel pathways: a morpho-orthographic decomposition pathway and a whole-word processing pathway. Any input letter string is analysed initially on the basis of its orthographic form and decomposed into morphemic subunits. At this level, derived words (*clean-er*, *re-late*), pseudo derived words (*corn-er*, *re-late*) and morphologically complex nonwords (*vilb-er*, *warn-ish*) are decomposed into smaller morphemic units. The parsed morpho-orthographic representation units then send activation to the orthographic lexicon. Here, words (*warn*) are successfully mapped onto their lexical entries, whereas the mapping of nonwords fails (*vilb*). Simultaneously, any existing letter string (e.g. *cleaner*, but not *vilber*) is mapped, via the whole-word pathway onto the orthographic lexicon in its entire form. From the orthographic lexicon, activation feeds into higher more abstract representations leading to the decomposition of semantically transparent morphological structures into morpho-semantic units. The morpho-semantic units feed back onto the lexical level and allow the activation of lexical entries with related semantic representations.

The evidence for semantic transparency effects revealed in Chapter 4 and 5 is also consistent with *form-then-meaning* theories proposing that an early morpho-orthographic processing level is followed by a later morphological processing stage at which the reading system generates semantic activations to analyse the semantic compatabily of morphemic sub-structures (e.g. Rastle & Davis, 2008; Taft & Nguyen-Hoan, 2010). For instance, Rastle & Davis (2008) propose that an early morpho-orthographic segmentation stage (decomposing any letter string with a morphological surface structure) is followed by a later stage of morpho-semantic segmentation (decomposing true morphological structures only). A graphic illustration of this proposal is represented in Figure 4.

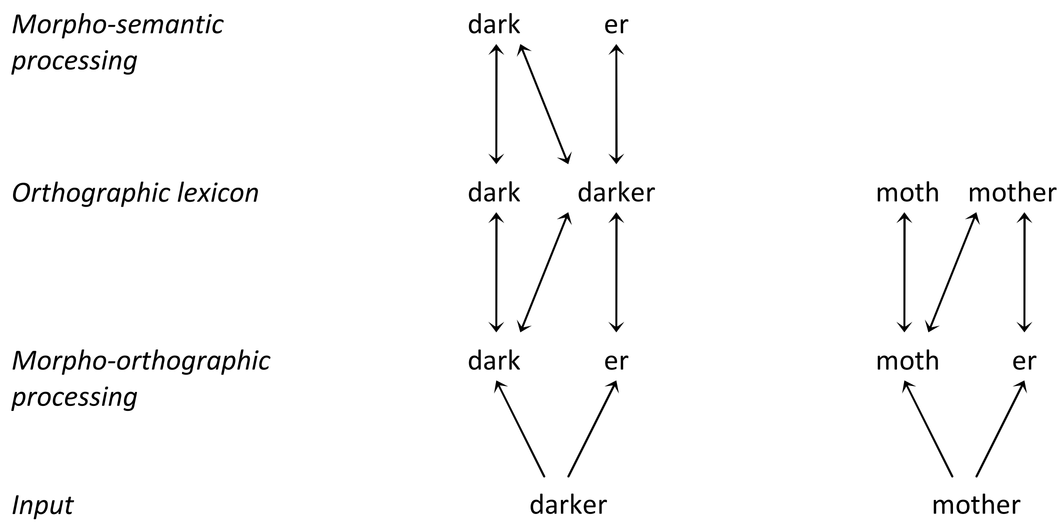

Figure 4: A *form-then-meaning* account of morphological processing proposing (i) an early level of morpho-orthographic decomposition followed by (ii) a later level of morpho-semantic decomposition (e.g. Rastle & Davis, 2008).

An alternative account which also considers that words are always initially analysed on basis of purely structural information is one proposed by Taft (2003; see also Taft & Nguyen-Hoan, 2010). Taft and Nguyen-Huan consider that words are always initially decomposed into smaller form units (*moth* + *er*). The purely stuctural processing units then send activation to a lemma level at which stem morphemes (*dark*) and derivational morphemes (*darker*) are represented (see Figure 5). Inflectional morphemes (e.g. *walks*, *walked*) are not represented at this level. Derivational and pseudo-derivational morphemes are activated via their morphemic form units. At the lemma level, semantically transparent morphological derivations (*dark* and *darker*) are connected via links between abstract lemmas representations, whereas no such links exist between semantically opaque morphological structures (*moth* and *mother*). For instance, the activation of the lemma of *darker* will send reinforcing activation to the lemma of *dark*, leading to greater activation pattern for truly morphological stems (e.g. *dark* as in *darkness*) as compared to pseudo-morphological stems (*moth* as in *mother*).

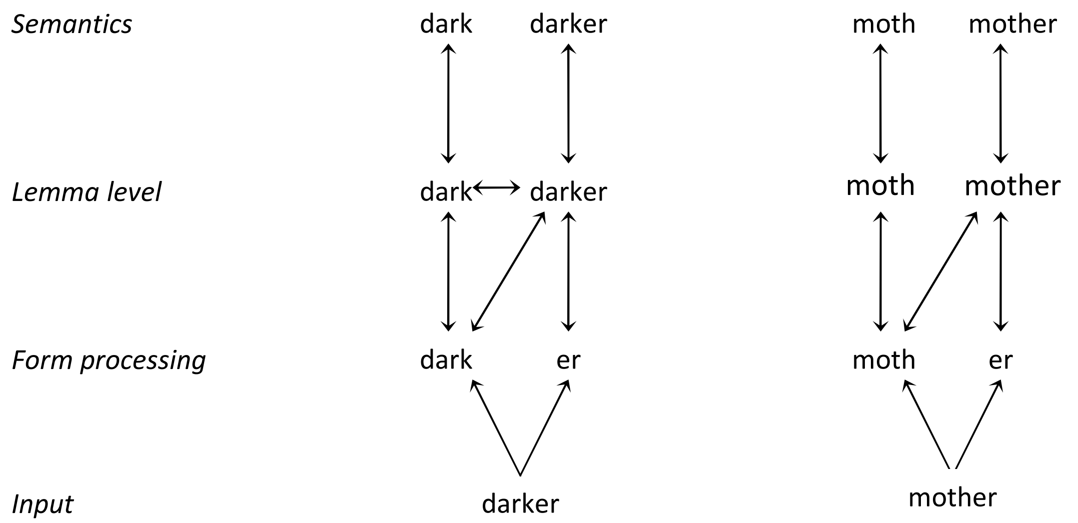

Figure 5: Model of morphological representation, based on Taft & Nguyen-Hoan (2010).

Given that the accounts presented in Figure 4 and 5 both consider that semantically transparent morphological structures benefit from activations arising at higher-level lexical and/or semantic processing stages, they can account for the graded effects of priming observed in Chapter 4 and 5.

Positional encoding of morpho-orthographic units during reading

A fourth goal of the present thesis was to more precisely locate the stage of processing at which morpho-orthographic processing occurs. To achieve this goal Chapter 3 examined whether masked morphological priming occurs with suffixed transposed-letter nonword primes (*wranish-WARN*), relative to a non-suffixed control condition (*wranel-WARN*). TL-priming was obtained in the suffixed, but not in the non-suffixed condition, which extends previous morpho-orthographic processing studies (Longtin & Meunier, 2005; McCormick, Rastle, & Davis, 2008; Rastle & Davis, 2008) to the transposed-letter priming domain. This research clearly suggests that morphological decomposition is triggered by an automatic morpho-orthographic parsing mechanism operating at very early orthographic processing stages while letter-position coding is not yet fully resolved. These findings further indicate that morphemic information and letter-position are both simultaneously encoded at a pre-lexical stage in the human reading system.

These findings have further implications for theories of letter-position coding (Davis, 2010; Whitney, 2001) suggesting that the letter position coding system does not solely operate on the basis of matching input letter strings onto matching lexical entries, but that there is an additional mechanism that allows for the decoding and stripping of affixal sequences while the letter position coding system simultaneously tries to produce a suitable match. That is, orthographic analysis does not uniquely rely on the coding of lower-level visual processing features, as the encoding of letter-identity and letter-position may already be morphologically informed. These findings are problematic for current letter position encoding theories, such as Open-Bigram theories (Grainger & Whitney, 2004; Schoonbaert & Grainger, 2004) and Spatial Coding theories (Davis, 1999, 2010). Both types of theories would generate a successful match, not only between *wranish* and *warn*, but also between *wranel* and *warn*, and therefore cannot account for the different pattern of priming observed. Neither model can explain why the activation of the target stem *warn* is only successful when presented in a morphologically complex context, but not when there is a non-morphological relationship between the prime and the target.

Following the English studies reported above (Chapter 3), we conducted a related study, in Spanish (Chapter 4). The findings of Chapter 4 show that stem-target recognition is significantly facilitated by the prior presentation of a semantically transparent affixed TL-nonwords prime (*d**lo**oroso-DOLOR*). However, in contrast to the results obtained in English, the Spanish study did not reveal evidence for masked transposed-letter nonword priming (*t**to**alito-TOTAL*). One explanation for the different pattern of results may be due to the differences in prime presentation durations. While in the English study (Chapter 3) primes were presented for only 40 ms, the Spanish study (Chapter 4) used prime presentation durations of 53 ms. The longer stimulus exposure in the

Spanish study might have (i) allowed a rapid advance of stimulus processing to higher processing levels, and (ii) thus entailed a weakening of morpho-orthographic activation pattern. Alternatively, it is also possible that the different pattern of priming can be attributed to language-specific differences between English and Spanish or are due to differences in statistical power (40 Spanish participants compared to 120 English participants). One interesting continuation of this work would be to collect larger data samples of the Spanish population to specifically compare affixed TL-words (*d**lo**oroso*) and affixed TL-nonwords (*t**to**alito*), using a combined experimental design.

Developmental aspects of morpho-orthographic and morpho-semantic processing

Another goal of this thesis was to investigate morphological processing in developing readers, specifically to examine (i) at what age in reading development morpho-orthographic processing mechanisms first become automatised and to test (ii) the strategies that children might use to acquire morphological knowledge (see Chapter 5). A masked primed lexical decision study was conducted with two groups of developing readers (Year 3 [age 8-9] and Year 5 [age 10-11]), replicating Rastle et al.'s (2004) design. Unlike the results obtained with adults, the developmental data revealed significant priming only in the truly suffixed condition (*golden-GOLD* vs. *frosty-GOLD*), but not in the pseudo-suffixed (*mother-MOTH* vs. *greedy-MOTH*) or non-suffixed condition (*spinach-SPIN* vs. *magical-SPIN*), in both age groups. As outlined in Chapter 5, the developmental data provide evidence for a morpho-semantically based decomposition mechanism in young readers. However, given that even in the more advanced age group of Year 5 readers no evidence for pseudo-suffixed priming was found, this indicates that automatic morpho-orthographic decomposition does not occur until a relatively late stage in reading development.

Moreover, the follow-up analysis of the developmental data in Chapter 5, based on the hypothesis proposed by Rastle & Davis (2008), revealed greater magnitudes of priming for prime-target pairs sharing a high proportion of semantic overlap (e.g. *flying-FLY*) than for those with a low proportion of semantic overlap (e.g. *moody-MOOD*). In addition, high suffix frequency primes produced greater magnitudes of truly and pseudo-suffixed priming compared to low suffix frequency primes. The results presented in Chapter 5 thus suggest that children use (i) form-meaning regularities and (ii) high-frequency letter sequences to group letter strings into morphemic clusters.

These data provide important insights to the development of automatic, unconscious aspects of morphological processing in young readers. Interestingly, it can be ruled out that children uniquely relied on learning letter probabilities, such as suffix and morpheme-boundary bigram frequencies. Our findings suggest that the acquisition of the ability to morphologically decompose words begins with the memorization of morphologically complex full forms (e.g. *teacher*, *teaching*, etc.). Then, through repeated exposure to form-meaning regularities (e.g. *teach-er*, *farm-er*, *mix-er*, etc.) and highly frequent letter sequences (e.g. *er*, *ing*, etc.), children begin to reach a more abstract level of understanding of morphological structures, which will eventually allow them to recognize orthographic similarities across different morphologically related words. This will result in the acquisition of a purely structural morpho-orthographic parsing mechanism, applied to every letter string with a morphological surface structure (e.g. *moth-er*, *corn-er*, *numb-er*, etc.).

Future prospects and final conclusions

The research presented in this thesis advances our understanding regarding the type of information and mechanisms that children and adults use to morphologically decompose words. A number of aspects remain subject to future investigations, these are briefly outlined below.

Morphological decomposition in the absence of orthographic transparency. Until now, relatively little attention has been directed to whether any sort of morphological decomposition mechanisms exist that operate in the absence of orthographic transparency. This is a difficult question to investigate, because by definition, morphologically related words at least partially overlap in form (e.g. *walk/walked*, *adore/adorable, jog/jogger,* etc.). Exceptions, however, are irregularly inflected words which share the same meaning, but not the same orthographic form (e.g. *give, gave, etc.*).

Recently, Crepaldi, Rastle, Coltheart & Nickels (2010) carried out a lexical decision experiment to investigate morphological processing of irregular inflectional forms in the context of masked priming. The results showed that target words were classified faster when preceded by an irregularly inflected prime (*fell-FALL*) than when preceded by an orthographically related (*fill-FALL*) or unrelated prime (*hope-FALL*). Moreover, pseudo inflected prime-target pairs (*raid-RAY*) did not produce any priming, indicating that the obtained effects cannot be related to sub-regular orthographic patterns. Crepaldi et al. (2010) propose the existence of an intermediate lemma level which operates between morpho-orthographic decomposition stages and higher semantic processing levels (see also Taft, 2003, 2004). It is suggested that at this level in the reading system, inflected word forms (e.g. *fell* and *falls*) and their stem morphemes (e.g. *fall*) are mapped onto the same lemma node. It remains unclear exactly how lemma representations are defined during reading. Future research is needed to more clearly differentiate between lemma-based processing mechanisms and other morphological processing schemes during visual word recognition.

Cross-linguistic aspects of morphological processing. For future research, it may also be of interest to systematically conduct cross-linguistic investigations to approach a more generalistic language-independent understanding of morphological processing. Findings from Semitic languages such as Hebrew (Frost, Forster, & Deutsch, 1997) or Arabic (Boudelaa & Marslen-Wilson, 2001) need to be carefully distinguished from languages with linear morphology such as English and German. As Frost, Deutsch & Forster (2000) pointed out, the highly productive nature of Semitic morphology might suggest that morphological decomposition relies on semantic transparency to a lesser degree than in languages in which the transparency of morphological structure is less predictable. Moreover, different degrees of orthographic transparency may also affect the nature and development of language-specific morphological systems. Different degrees of orthographic opacity have been found to play a significant role in children's ability to learn how to correctly spell words. For instance, it was shown that children acquiring languages with transparent orthographies generally perform better at reading words at nonwords then children acquiring languages with opaque orthographies (e.g. Spencer & Hanley, 2003). It is thus possible that the transparency of different alphabetic orthographic systems influences the strategies that children might use to acquire morphological knowledge, as well as the techniques that adults use to recognise written words. Systematic cross-linguistic comparisons are therefore an essential aim for future investigations, taking morphological productivity and orthographic transparency into account.

Neural correlates of morphological processing. To date, a number of studies have used neurophysiological measures (electroencephalography [EEG] & magnetoencephalo-graphy [MEG]) to test morphological processing in adults. EEG, for instance, is typically used to record electrophysiological brain activity at the scalp's surface. EEG has the advantage that the electrical signals can be measured in real time, elicited by externally observable signals (*event-related potentials* [*ERPs*]). Due to the high temporal resolution, this provides a realistic image of the event-related brain activity. Neural priming has previously been indexed (Lavric, Clapp, & Rastle, 2007; Morris, Frank, Grainger, & Holcomb, 2007) by a reduction of the N400 ERP component associated with targets preceded by related primes (*cleaner-CLEAN/corner-CORN*), as compared to targets preceded by unrelated primes (*walking-CLEAN/singing-CORN*). By drawing upon neuro-imaging techniques, greater knowledge of the cognitive mechanisms and representations of language processing can be achieved, through informing and evaluating the understanding of morphological processing mechanisms. Until present, relatively little has been known about the spatio-temporal dynamics of morphological processing in the brain. However recently, electophysiological techniques have been more commonly applied to studying cognitive development in young children (e.g. Mahajan & McArthur, 2011; McArthur, Atkinson, & Ellis, 2011). By exploring how unconscious exposures to morphological manipulations influence behavioural performance in young children, future research can gain insights into cognitive development of the morphological parsing system.

Developmental aspects of morphological processing. This thesis has presented new evidence supporting the role of morphological processing in reading development. Yet it remains uncertain at which age in reading development morphological decomposition first becomes automatised. Future research should focus on examining children at a more advanced stage than Year 5, so as to determine the youngest age at which form-based morphological decomposition becomes evident. Moreover, while significant correlations were reported between aspects of orthographic and semantic processing and morphological knowledge in Year 3 and Year 5 readers, only tentative conclusions regarding the precise type of information triggering morphological decomposition in young children can be drawn. Although, this initial study provides some initial insights into how and when developing readers learn to detect and analyze morphological structure, further research is needed to more systematically investigate the role of letter probabilities (e.g. suffix frequencies, boundary bigram frequencies) during the development of morphological knowledge. Future work should also use a broader spectrum of methodological designs, such as unmasked priming, cross-modal priming, eye-tracking, and electropysiological measures, to examine early unconscious aspects of morpho-orthographic and morpho-semantic processing mechanisms in young readers.

Summary. The data reported in this thesis provide important insights into morphological processing mechanisms in both children and adults. While the examination of morphological processing during visual word recognition in adults has revealed evidence in support of a morphological segmentation mechanism which is guided by the orthographic analysis of the letter string, it has been demonstrated that this structural decomposition mechanism is not present until a relatively late stage of reading development. This thesis further shows that morphological analysis in both children and adults benefits from higher-level processing levels, showing that lexical and semantic representations provide an important basis for analyzing and evaluating morphological information.

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Appendix

Pages 174-179 of this thesis have been removed as they contain published material under copyright. Removed contents published as:

Beyersmann, E., Castles, A. & Coltheart, M. (2011) Early morphological decomposition during visual word recognition: Evidence from masked transposed-letter priming. *Psychonomic Bulletin & Review*, vol. 18, 937 (2011). https://doi.org/10.3758/s13423-011-0120-y

MACQUARIE
UNIVERSITY ~ SYDNEY

13 December 2006

Professor Max Coltheart
Macquarie Centre for Cognitive Science
Division of Linguistics and Psychology

Reference: HE24NOV2006-R04946

Dear Professor Coltheart

FINAL APPROVAL

Title of project: ***Recognizing, understanding and naming pictures and words***

Thank you for your recent correspondence. Your responses have satisfactorily addressed the outstanding issue raised by the Committee. You may now proceed with your research.

Please note the following standard requirements of approval:

1. Approval will be for a period of twelve months. At the end of this period, if the project has been completed, abandoned, discontinued or not commenced for any reason, you are required to submit a Final Report on the project. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. The Final Report is available at http://www.ro.mq.edu.au/ethics/human/forms
2. However, at the end of the 12 month period if the project is still current you should instead submit an application for renewal of the approval if the project has run for less than five (5) years. This form is available at http://www.ro.mq.edu.au/ethics/human/forms. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report (see Point 1 above) and submit a new application for the project. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).
3. Please remember the Committee must be notified of any alteration to the project.
4. You must notify the Committee immediately in the event of any adverse effects on participants or of any unforeseen events that might affect continued ethical acceptability of the project.
5. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University (http://www.ro.mq.edu.au/ethics/human).

If you will be applying for or have applied for internal or external funding for the above project **it is your responsibility** to provide Macquarie University's Research Grants Officer with a copy of this letter as soon as possible. The Research Grants Officer will not inform external funding agencies that you have final approval for your project and funds will not be released until the Research Grants Officer has received a copy of this final approval letter.

Yours sincerely

Dr Margaret Stuart
Director of Research Ethics
Chair, Ethics Review Committee [Human Research]

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