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Towards a comprehensive understanding of reading

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Reading is easy, and thinking is hard work, but the one is useless without the other.

Lord Bryce

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Abstract

Reading is an activity in which humans routinely engage in on an everyday basis. It is thus not surprising that the question of how we identify and process words has been one of the central interests of psycholinguistic research in the past decades. Indeed, the science of reading has progressed enormously in this time, and we have gained important insights into visual word identification. However, our current understanding of word identification is difficult to extend to text reading—both experiments and theories focus primarily, if not exclusively, on out-of-context individual words. Instead, text reading has been extensively explored through the models of eye movement control in reading. However, their focus lies primarily on the decision of when to move the eyes to the next word and the nature of attention allocation, while they tend to stay clear of the lexical dynamics, described in models of single word processing. While both these fields importantly advanced our knowledge, the entire complexity of reading process surely cannot be addressed while they are kept in isolation. Recently, a shift towards a more integrated approach, joining the findings of both fields, has started to emerge. At the same time, the constant development of new techniques now allows us to address reading under more integrated and natural experimental conditions.

We make use of these in the present thesis, where we follow the path from the study of words in isolation towards more ecologically valid study of word processing during sentence reading. Throughout the present work, we approach the reading research in three steps. We start from the individual word processing—in chapter 2, we introduce a masked morphological priming study, in which we address the question of existence of stem and inflectional suffix priming. Following, we move on towards a more integrated approach of visual word identification and text reading—in chapter 3, we study cross-word semantic and morphological priming within sentences in a natural reading, eye tracking experiment. Finally, we try to apply this integrated approach to the study of neural signatures during natural reading—in chapter 4, we use the same cross-word semantic and morphological priming paradigm as in

the previous chapter, but we introduce it in a natural sentence reading study in which we simultaneously record the eye movements and electroencephalogram.

Taken together, the present work presents three different approaches to the study of morphological and lexical-semantic priming. Throughout these studies, no evidence in support of (inflectional) morphological priming was observed, while solid effect of lexical-semantic priming was observed both in words in isolation, as also in a natural sentence reading. With this, our work indicates that inflectional morphemes behave differently from stems and derivational morphemes in complex word recognition.

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General introduction

Reading is an activity in which humans engage in on an everyday basis, without much effort and often without giving it too much thought. It is thus not surprising that most people (once they successfully acquire reading skills) would refer to this activity as easy. Yet, it is in fact not easy. Rather, it is a very complex skill (Rayner and Reichle, 2010), arguably the most complex skill in which humans routinely engage in (O'Shea and Huey, 1908; Rayner and Pollatsek, 1989) and a demanding cognitive task, which simultaneously unfolds at several linguistic levels (Dimigen et al., 2011).

This is revealed already when asking a seemingly simple question: What do readers really read when they read a single word such as, e.g., 'WRITER'? Surely, they read a sequence of graphemes—representing the form level. Also, they read a word as a distinct and familiar object—representing the lexical level. They also read two independent and meaningful units, i.e. 'WRITE' and 'ER'—representing the morphological level. And they also read a word, providing a piece of meaning, which connects to their experience of the real world—representing the semantic level. A successful reader's processing system would thus have to simultaneously address all these different levels. How does the human reading system deal with this challenge?

1.1 Visual word recognition in words in isolation

In the past decades, this question has been of central interest to both the theoretical and empirical psycholinguistic research. Starting in the 1960s, early work in the field dealt with this challenging question through the study of words in isolation (Lupker, 2005; Rastle, 2007), which remained the central interest of the reading research until the present day.

1.1.1 Models of single word processing

The past decades of theoretical research have brought to life numerous models of single word identification. Most of these early models (such as, e.g., Gough, 1972; Morton, 1969; Rastle, 1974) adopted the view that the information processing reveals through different stages, which follow each other serially. Through this system, the information only flows in a forward direction (Lupker, 2005).

The first group of models that adopted this view was built on the assumption that each of the processing stages must be completed before the next one could begin. Essentially, the models assumed that a stage was ready to pass information forward only when its activation level reached a certain threshold (Lupker, 2005); these models thus became known as 'thresholded'. One of the models that best represents this assumption is the *The bin model* (Forster, 1976, 1989), which suggests that readers recognize a word by comparing a prelexical code against a set of lexical codes, stored in lexical memory, until a match is obtained.

These early models importantly advanced the field and were able to account for a phenomenon, widely observed in the empirical research of that time—the word frequency effect, the fact that high frequency words are responded to more rapidly than low frequency ones (e.g., Forster and Chambers, 1973). But at the same time, these models also faced a major drawback. They were namely not able to account for effects of the higher-level information on the lower-level processing (Lupker, 2005). The classic example of such effects is the word superiority effect, the fact that people are better at recognizing the letters presented within words as compared to letters, presented either in isolation or within nonwords (e.g., Cattell, 1886; Reicher, 1969; Wheeler, 1970).

The second group of models better deals with this latter effect. These models adopted the assumption of cascaded processing, in which the information passes between stages as soon as the information at one stage begins to be activated (e.g., Harley, 2001; Lupker, 2005). Among these models, the *Interactive activation model (IAM)* (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982) is the most influential. This model includes different levels of processing: feature, letter, and word level, as well as also a higher-level processing that provides a 'top-down' input to the word level (McClelland and Rumelhart, 1981). During processing, the information thus not only flows forward, 'bottom-up', i.e., from the feature to the letter and word level, but also in the opposite direction, 'top-down', i.e., from higher-level processing to word level to other lower-level representations. The perception is further assumed to be an interactive process, in which the 'top-down', conceptually driven processing, and 'bottom-up', data driven processing jointly contribute to the perception. Additionally, the model also assumes inhibition between representations at the same level (e.g., Harley, 2001; Lupker, 2005). This model thus represents the first implementation of activation and inhibition processes, which offered a solid starting point for the models to follow, and further inspired several other models, such as e.g., the *Multiple Read-Out model* (Grainger and Jacobs, 1996) and *Dual Route Cascaded (DRC) model* (Coltheart et al., 2001).

The latter is one of the most influential models that builds on the assumptions of the IAM (Harley, 2001). It focuses on reading aloud and builds on the assumption that the word's pronunciation can be generated in two separate routes: (i) through the application of grapheme-to-phoneme correspondence rules that convert the individual graphemes (i.e., letters of the read word) into their corresponding phonological representations (i.e., phonemes); and (ii) through a more direct mapping of word's spelling onto its pronunciation. Another fundamental assumption of the model is that orthographic and phonological forms of words are represented holistically, as discrete processing units in the lexicon, which enables known words to be pronounced by mapping their graphemes onto the orthographic unit that provides the best match, and in turn directly activates the corresponding phonological unit. Importantly, the assembled and direct routes operate in parallel and jointly determine the final pronunciation of the word (Rayner and Reichle, 2010).

However, while DRC's (as well as all the other aforementioned models') main assumption was that the basis of the word recognition is the isolation of the relevant lexical unit, a number of models opposed this idea of lexical units. Instead, they proposed that the lexical system is composed out of sets of distributed, subsymbolic codes, which represent the attributes of the known words (Lupker, 2005). These models thus assumed that the word identification encompasses different types of lexical information which jointly contribute to the development of constraints on as well the pronunciations as also the meanings (Rayner and Reichle, 2010). These models are marked as parallel distributed processing models, and are typically represented with a triangle framework (e.g. Lupker, 2005; Rayner and Reichle, 2010)—which is why they have become known as 'triangle models' (such as, e.g., Harm, 1999; Plaut et al., 1996; Seidenberg and McClelland, 1989).

Despite the fact that several models fit into this group, the first and best known one among them is the Seidenberg and McClelland (1989) model. This model assumes that word identification and pronunciation involve three different types of mental representations: ortographic, semantic, and phononological one. The units of different types are assumed to be interconnected with feedback connections, which, crucially, contain the lexical information.

The strength of the connection is assumed to be enhanced through the repeated experience with the words, which offers an explanation for the observed word frequency effect (Rayner and Reichle, 2010).

All the aforementioned models importantly advanced the field of individual word recognition. However, in their goal to simulate the mechanics of lexical processing and reading aloud, they typically didn't devote much attention to the orthographic processing. Rather, they adopted the most simple assumption—absolute letter position coding (e.g., Snell et al., 2018b). With that, they assumed that a stimulus with a specific letter at a certain position would only activate words that have that same letter at that same position (e.g., Davis and Bowers, 2004). But several empirical phenomena speak against this assumption (e.g., Davis and Bowers, 2004; Snell et al., 2018b). One such example is the transposed-letter (TL) effect, the fact that words which are almost identical—apart from the transposition of the two of their adjacent letters (e.g., TRIAL-TRAIL)—influence each other's processing. For example, in lexical decision tasks the responses to TL nonwords (e.g., WODNER), which are derived from a valid word (e.g., WONDER) are slower and less accurate, compared to responses to nonwords without the TL word pair (e.g., LODNET) (Davis and Bowers, 2004).

This empirical phenomenon was taken as evidence against absolute letter position coding, and triggered the need for models that would allow more flexible, relative position coding. This inspired a new generation of models, such as, e.g., the open-bigrams models (e.g., Grainger and Heuven, 2011; Whitney, 2001). These assume that word stimulus activates specific nodes, which represent relative position of within-word letter pairs. According to these models, a word stimulus such as, e.g., *cake*, would activate several nodes (i.e., nodes for *ca, ck, ce, ak,* and *ke*), which would in turn activate all lexical representations to which they belong (Grainger and Heuven, 2011; Whitney, 2001) (e.g., the node *ca* would not only activate the lexical representation for *cake*, but also for *cat* and crab, among others).

With this approach, the open-bigram models can account not only for the above mentioned TL effect, but also for a some more recent empirical findings, such as, e.g., the ones obtained with flanking letters lexical decision paradigm (e.g., Dare and Shillcock, 2013). This paradigm revealed that lexical decision about the word, presented at the position of the eye's fixation (e.g., cake), is faster and more accurate when the word is flanked with two related letters on each side (e.g., *ca cake ke*), compared to when it is flanked by unrelated letters (e.g., *op cake ra*). Importantly, the order of the flanks does not seem to matter—e.g., for the previous example, the *ca cake ke* triggers the same facilitation effects as *ca cake ke*, providing additional evidence in support of relative letter position coding[1] (Dare and Shillcock, 2013).

1.1.2 Priming and masked priming research

Alongside the theoretical research, empirical research of the past few decades also importantly advanced our understanding of single word processing. A very insightful approach in addressing this issue have been various priming paradigms. In the past decades, these have become one of the most popular techniques of the psycholinguistcs, with their popularity being at least partially owed to their procedural simplicity (Spruyt et al., 2011).

In a typical priming language study, the participants are simply presented with a series of trials, consisting of the presentation of two consecutive words—the prime (presented first) and the target (presented second). Crucially, the relationship between the two words in the mental lexicon is tackled by the manipulation of their relationship (e.g., the two words can be semantically related (e.g., doctor-NURSE) or unrelated (e.g., dog-NURSE)) and the

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[1] Note, however, that a recent study suggests that when longer target words and flanks are used (six and three letters long, respectively) the order of the flanks does seem to play a role—the facilitation was observed only when the order of the flanks was consistent with the target word (e.g., *tar target get)* (Snell et al., 2018a). This could suggest that longer words bear more processing weight, bringing in play additional processing mechanism, which might potentially allow for some knowledge of absolute letter position (Snell et al., 2018b).

observation of how the differently related primes influence the responses to the targets (e.g., Boudewyn et al., 2012; Camblin et al., 2007; Sebastiani et al., 2015). What is typically observed is that if the two words are somehow related (e.g., semantically or morphologically related) the response times and accuracy are improved, relative to when the two words are not related (e.g., Spruyt et al., 2011)—which is known as the priming effect.

This effect has been observed in a number of different priming paradigms, including the overt (in which the participants are aware of the presentation of both words, the prime and the target; e.g., Raveh (2002)), long-lag (in which the prime and the target are not presented one after another, but are rather separated by other intervening items; e.g., Stanners et al. (1979); Zwitserlood et al. (2000)), cross-modal priming (in which the prime and the target are presented in different modalities, such as e.g., auditory presentation of the prime and written presentation of the target; Marslen-Wilson et al. (1994)), and masked priming (e.g. Chateau et al., 2002; Crepaldi et al., 2016; Dominguez et al., 2010; Giraudo and Grainger, 2003; Rastle et al., 2000).

The latter is particularly interesting, as it permits to observe strategy-free responses (Forster, 1998). Namely, the prime (e.g., dealer) is typically presented between a forward pattern mask (e.g., #####) and the target stimulus (e.g., DEAL), which functions as a backward mask. Additionally, the prime is presented with very short duration (typically $<$ 50ms), which in combination with the two masks disables its conscious perception (i.e., the prime is 'masked') (Dominguez et al., 2010)—and with this it also prevents the participants from developing response strategies. Thus, this method is considered a more pure way to tackle the lexical processing (e.g., Forster et al., 2003; Forster and Davis, 1984). As such, masked priming paradigm gained a lot of popularity and has been used with different prime-target relationships, such as, e.g., semantic (e.g., doctor-NURSE; e.g., Balota (1983); Carr and Dagenbach (1990); Forster and Davis (1984); Marcel (1983)), repetition (nurse-NURSE; e.g., Bodner and Masson (1997); Forster and Davis (1984)), and morphological (e.g. nursing-

NURSE; e.g., Forster and Azuma (2000); Rastle et al. (2004).

Morphological processing

In the past four decades, morphological processing has been one of the most widely studied topics regarding visual recognition of written words, with the pioneering work in this field emerging as early as in the 1970s (e.g., Taft and Forster, 1976). Since then, the vast body of literature (e.g., Crepaldi et al., 2016; Feldman, 2000; Forster et al., 1987; Grainger et al., 1991; Neely, 1977; Rastle et al., 2000) consistently reports robust priming effects when the prime and target share a stem (e.g. dark-DARKNESS; Amenta and Crepaldi (2012); Marslen-Wilson (2007)).

These findings have been so consistent that they have led to what has now become a broadly accepted consensus—words with morphological surface structure (i.e., words that can be parsed into known morphemes, such as stems and affixes; Rastle (2007)) are during processing divided in and analysed through their constituent morphemes (e.g., dark + ness), which in turn play a crucial role in the word's identification (e.g., Bradley, 1979; Rastle, 2007, 2011; Taft and Forster, 1976).

Despite the fact that stem priming effect is one of the most well-established single word morphological processing phenomena, we cannot talk about the morphological priming effect without giving attention also to the other types of morphemes—prefixes and suffixes.

Despite being less researched than the stem priming effect, the prefix priming effect is also a well-explored phenomena (e.g., rebuild - REACTIVATE), with a substantial number of studies offering convincing support for its existence (e.g. Chateau et al., 2002; Dominguez et al., 2010; Giraudo and Grainger, 2003; Reid and Marslen-Wilson, 2000, 2003). However, the image becomes less clear when addressing suffix priming effect.

Several studies approached the issue of suffix priming (e.g. singing-WALKING)—but yielded conflicting results (i.e., priming effects have been found in, e.g., Duñabeitia et al. (2008), but not in e.g., Giraudo and Grainger (2003)). However, these studies used real word primes, which could potentially lead to the lexical competition between the primes and targets (e.g., Crepaldi et al., 2016; Davis and Lupker, 2006; Segui and Grainger, 1990), leading to uncontrolled effects on the priming effect. When, instead, nonword primes were used, the derivational suffix priming effect was more reliably observed (Crepaldi et al., 2016).

However, all these studies used derivational affixes. Inflectional affixes are much less studied, and there are several reasons to believe things may be different on this front. Linguists draw a strong dichotomy between inflection and derivation (e.g., Haspelmath, 2010): (i) inflection never indicates the change of grammatical category (e.g., dog-dogs) while derivation always does (e.g., dark-darkness), (ii) inflection is typically more semantically transparent (relationship between dog-dogs is identical to the relationship between car-cars), while derivation is more idiosyncratic (e.g., 'a gardener' is a person who takes care of the garden, while 'a juicer' is a kitchen appliance that makes juice; e.g., Crepaldi et al. (2010)), and (iii) inflection never introduces a new meaning to their base morphemes, while derivation can (e.g., person-personal).

Despite this fact, there is a large absence of empirical evidence regarding inflectional suffix priming effects. A possible reason for this lack of evidence could be due to the fact that inflectional suffix priming effects, if they exist at all, might be difficult to detect. They may namely be relatively small, compared to the other morphological priming effects, such as e.g., lexical stem priming. There are several reasons why this could be the case. Firstly, inflectional affixes tend to have high frequency—and identity priming effects have been shown to be smaller for high frequency items than lower frequency ones, which is known as reverse base frequency effect (Taft, 2004). Further, inflectional suffixes do not have an autonomous meaning, since they are a functional rather than lexical items (cf., stems and prefixes do carry a meaning). As such they are neutral in valence, low in arousal, and low in concreteness, all of which have been suggested to contribute to word recognition speed (e.g., Kuperman et al., 2014).

Nevertheless, a few studies addressed the question of inflectional suffix priming in left-to-right languages, indicating that it is possible to detect such effects. One of this studies did observe (modest) inflectional suffix priming effect, but it could not reliably determine weather it is truly inflectional in nature (Reid and Marslen-Wilson, 2000). Another study found significant priming effects with verbal, but not with nominal inflectional suffixes, but was not able to rule out the possibility that potential nominal priming effect was overridden by the structural priming effect (VanWagenen and Pertsova, 2014). These few studies[2] thus do not reveal a clear image, and leave the topic of inflectional suffix priming largely under-investigated.

This is where we have started the research path described in this thesis. The realization that at present this topic remains largely unaddressed led us to the development of our first study, in hope to provide further insights into processing of inflectional morphology. To this end, we based our research on one of the most well established paradigms, which was shown to present a solid approach to the study of morphological processing: masked priming in words in isolation (e.g., Crepaldi et al., 2016; Dominguez et al., 2010; Duñabeitia et al., 2008; Feldman, 2000; Giraudo and Grainger, 2003).

Through our work, however, we have started to realize that this paradigm, despite the comforting fact that it is well-established and has importantly advanced our knowledge regarding inflectional morphological processing, also has its disadvantage. It namely addresses language processing in a very limited linguistic context of two words, and in the frame of a rather unnatural task, where participants are typically asked to decide whether the presented

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[2] Another study in left-to-right languages was conducted, but has insofar only been published as an abstract of a conference poster presentation. Similarly to VanWagenen and Pertsova (2014), this study also observed priming effects with verbal, but not with nominal inflectional suffixes, but was not able to clearly assign the source of the observed discrepancy (Smolik, 2010).

word is real or not. As such it differs quite a lot from the actual reading experience for which human cognitive system is trained for and into which it actively engages in on an everyday basis. This has led us to take our research further and to ask ourselves an important new question: would the observed morphological priming effect also emerge in natural reading?

1.2 Word processing in natural reading

With this question in mind, we have decided to shift our attention from the studies of words in isolation towards the studies of sentence reading. Despite the fact that the first still prevail, more and more attention is lately given also to the latter—with the emphasis on the importance of ecologically more valid designs in studies of reading (e.g., Dimigen et al., 2011) and on the importance of a more integrative approaches to the studies of reading, that would bridge the gaps of addressing only one level of the complex reading system (e.g., Rayner and Reichle, 2010; Snell et al., 2018b).

1.2.1 Eye tracking research

When it comes to addressing reading in a more natural experimental setups, eye tracking seems to be a natural choice. This methodology allows to present complete sentences, rather than just individual words, while participants are simply asked to read for their comprehension. This method thus enables to address reading in an environment that is as close as possible to the actual, everyday reading experience, while it also allows to track and record the full complexity of eye movement behaviour with a millisecond precision.

The rationale behind this method is fairly straightforward: encountering any kind of processing difficulty during reading, such as e.g., processing of a long or less frequent word (e.g., Paterson et al., 2015; Rayner et al., 2011), dealing with temporary ambiguity (e.g., Binder and Morris, 2011; Rayner and Duffy, 1986; Rayner and Morris, 1991), or even facing individual's reading difficulties (such as dyslexia; e.g., Prado et al. (2007)), reflects in increase of fixation durations, as well as also in the number and probability of refixations and regressions to the earlier parts of the text.

This method has been proven to be extremely useful in addressing reading in more natural experimental setups. In fact, most of our understanding of how readers comprehend presented text is owed to the eye tracking studies. These have revealed that eye movements during reading are characterized by complex combinations of different eye movements, such as saccades (typically with a span of 8-9 characters; Rayner et al. (2001)), fixations (typically lasting 200-250ms; Sereno and Rayner (2003)) and refixations (typically on longer words; Paterson et al. (2015)), or less frequent words; Rayner et al. (2011)), word skips (with frequent and highly predictable words being skipped more often; Rayner et al. (2011)), and regressions back to the earlier parts of the text (about 10-15% of the time; Rayner (1993)).

Additionally, eye tracking confirmed that many phenomena, previously reported in words in isolation, are also observed in text reading. One such example is the fact that eye fixation durations in reading are reliably influenced by individual word's frequency (e.g., Inhoff and Rayner, 1986; Rayner and Duffy, 1986), such that low-frequency words result in longer fixation durations (e.g., Inhoff and Rayner, 1986; Rayner et al., 2004; Rayner and Duffy, 1986; Rayner et al., 2011; Staub, 2011). This word frequency effect offers a nice convergence between the findings in individual word identification setups and more natural reading paradigms. However, the latter reveal also other types of reading phenomena that extend beyond individual word identification, such as, e.g., the context-dependant predictability effect (e.g., Rayner et al., 2004, 2011), the fact that words, unpredictable in a given context, result in longer fixation durations (e.g., Rayner et al., 2004, 2011). Another class of effects that emerged in the eye tracking literature is related to effects that extend across consecutive words. One example of this class is the parafoveal preview effect, whereby fixations on word *n+1* become longer when the reader is denied a preview of the word in the parafovea (e.g., Veldre and Andrews, 2018). Another such effect, which goes hand-in-hand with the just described parafoveal preview effect, is also the foveal load effect—the finding that the difficulty of processing word n modulates the size of the parafoveal preview effect on word $n + 1$, such that the greater the processing difficulty of word n, the smaller the parafoveal preview effect on word $n + 1$ (e.g., Henderson, 1990; Veldre and Andrews, 2018).

These cross-word effects confirm that natural reading extends well beyond single word identification (as studied through words in isolation) and speak up to the importance of conducting the reading research in ecologically more valid designs.

1.2.2 Models of eye movement control in reading

This realization reflects also in the theoretical research of reading—in order to offer a more integrative approach to the modeling of reading (Rayner and Reichle, 2010), the newer generations of models largely focused on eye movement control in reading. These models started to appear in the 1980's and 1990's (such as, e.g., Just and Carpenter (1980); Reilly and O'Regan (1998); Suppes (1990)), but the real breakthrough happened in 1998, with the introduction of the *E-Z Reader* model (Reichle et al., 1998). In the years to follow, the *E-Z Reader* inspired several other models: *EMMA* (Salvucci, 2001), *SWIFT* (Engbert et al., 2005), *SERIF* (McDonald et al., 2005), *Glenmore* (Reilly and Radach, 2006), *SHARE* (Feng, 2006), and *Competition-Interaction* model (Yang, 2006). In contrast to some earlier, so-called ideal observer models, which aimed towards simulating optimal reading performance (such as, e.g., *Mr. Chips*; Legge et al. (1997)), these models aimed towards explaining actual performance of human readers. In so doing, they focused largely on the decision of when to move the eyes from one word to the next one, and the nature of attention allocation.

Out of the mentioned models, the two most prominent ones are the competitor models (Rayner and Reichle, 2010) *E-Z Reader* (Reichle et al., 1998) and *SWIFT* (Engbert et al., 2005). Both these models can account for several observations of the empirical eye movement research. For example, they successfully account for the influence of lower-level variables, such as visual acuity—the fact that the further the letters are from the position of where the eye is fixated, the harder they are to identify (e.g., Bouma, 1970; Nazir et al., 1991; Townsend et al., 1971). They also account for oculomotor constraints, such as landing-site distributions—the observation that the landing position on a word *n* depends on the launch distance of the saccade from the previously fixated word (most often, word *n-1*) and of the length of that word (e.g., Mcconkie et al., 1988). And they also account for lexical variables, such as the aforementioned word frequency effect (e.g., Inhoff and Rayner, 1986; Rayner et al., 2004; Rayner and Duffy, 1986; Rayner et al., 2011; Staub, 2011).

However, despite their similarities, the two models importantly differ in their assumption of how the attention is allocated. *E-Z Reader* assumes that attention is allocated serially, i.e., one word at a time. Thus, according to this model, the lexical processing of word *n+1* does not begin until the meaning of word *n* has been accessed (e.g., Rayner and Reichle, 2010; Reichle et al., 1998, 2009). Conversely, *SWIFT* assumes that attention is allocated in parallel, making it possible for several words to be identified simultaneously (e.g., Engbert et al., 2005; Kliegl et al., 2006, 2007).

The disagreement about the nature of attention allocation is not unique to the two models. This assumption is namely one of the most important distinguishing characteristics also of all the aforementioned models, based on which they could be divided into three different groups. While *EMMA* (Salvucci, 2001) joins in with the *E-Z Reader* (Reichle et al., 1998) in the assumption that the attention is allocated serially, *Glenmore* (Reilly and Radach, 2006) rather joins *SWIFT* (Engbert et al., 2005) in the assumption of parallel attention allocation. In contrast, *SERIF* (McDonald et al., 2005), *SHARE* (Feng, 2006), and *Competition-Interaction* model (Yang, 2006) form a third group, which builds on the assumption that attention plays no, or at best only a small role in guiding the reader's eye movement (Rayner and Reichle, 2010).

Despite their differences, all the aforementioned models importantly advanced our understanding of the reading processes. However, they all share a rather important disadvantage—they largely ignore the contribution of the models of single word orthographic processing. As such they step away from an integrative approach to the study of reading which could account for the full complexity of the reading system (e.g.. Rayner and Reichle, 2010; Snell et al., 2018b).

Recently, however, exceptions to this trend are starting to surface. One such example is the very recent model *OB1-Reader* (Snell et al., 2018b), which aims towards bridging this previously ignored gap between the models of single word processing and the models of the eye movement control in text reading. Very generally, the model successfully joins the main assumptions of relative position coding for single word recognition on the one hand, and of parallel attention allocation in text reading on the other hand (Snell et al., 2018b). With this, the model offers a new approach to the study of text reading and speaks up to the importance of a more integrated approach to this complex task.

1.2.3 Priming in natural reading

In our aim to shift our research from single word processing towards more natural reading paradigms, we followed in a similar spirit, but moved our focus away from the eye movements. Through semantic and morphological priming paradigm, we rather addressed more post-orthographic processing levels in lexical identification, and how they are affected by the engagement of the visual word identification system with multiple words in very rapid succession.

Studying semantic priming during sentence reading is of course not a new idea. Several eye tracking studies have previously addressed this issue, but either yielded conflicting results (semantic priming was reported in e.g., Blank and Foss (1978); Van Petten et al. (1997), but not in e.g., Duffy et al. (1989); Morris (1994)), or introduced a design in which observed semantic priming effect could not be reliably distinguished from online prediction of the upcoming word (e.g., Camblin et al., 2007; Carroll and Slowiaczek, 1986). On the other hand, morphological priming remains rather underinvestigated in natural sentence reading studies. Namely, the existing literature cannot reliably establish whether the observed priming effect is truly morphological in nature, or rather a more semantic priming effect, or even a combination of both (e.g., marshy-MARSH; Paterson et al. (2011)). In hope to shed new light onto the matter, we have developed a novel natural reading priming paradigm, which is virtually free of the confounds that affect the previously available data. Additionally, our design allowed us to address both semantic and morphological priming within the same stimuli set, which enabled us to explore also the interaction between the two priming effects.

Since this innovative design allowed us to address issues that were previously unadressed, we have decided to further exploit its benefits in our next research steps. We have thus asked ourselves yet another question—would it be possible to link the effects, observed on the behavioural eye movement level as tracked by the eye tracker, to the neural signatures of the priming effect in natural reading?

1.2.4 Neural correlates of reading processes

When addressing neural correlates of natural reading, eye tracking comes to our aid once again. This method alone of course does not offer any insight into neural activity, but its high temporal resolution does offer an opportunity for a valuable expansion, which, in turn, would allow to link the observed eye movements with the underlying neural correlates—if we simultaneously record the eye tracking and the electroencephalogram (EEG).

EEG, another technique with an excellent temporal resolution, is one of the most commonly applied methods for investigation of neural correlates of language processing. Namely, this recording of the intrinsic electrical activity in the brain also allows for recording of small potential changes in the continuous EEG signal, which occur as a neuronal response to the specific sensory stimulus—the so-called events. In the case of reading, such event is typically the presentation of a single word on the screen, while the neural correlates that align to this event are the so-called event-related potentials (ERPs). However, if we do not only record the EEG, but simultaneously also record the eye movements as tracked via eye tracker, these events no longer have to be locked to a predetermined onset of a stimulus on the screen. Instead, they can be locked to the specific eye movements, such as fixations on the individual words of the presented text (fixation-related potentials, FRPs). These act as natural EEG events, providing an exquisite opportunity to explore neural correlates of natural reading.

Maybe somewhat surprisingly, the coregistration of the eye movements and EEG is far from being a new method—it was first introduced as early as 1964 by Gaarder et al. (1964), who investigated whether there is a specific brain response following a saccadic eye movement[3]. More than 50 years ago, they were the first to observe the brain signature of a saccade, and suggested that its characteristics depend on the luminance of the presented stimulus (Gaarder et al., 1964).

While linking the eye movements to the brain responses may not be a recent idea, linking the eye movements during reading[4] to the brain signatures of language processing only emerged in the recent years (e.g., Dimigen et al., 2012; Henderson et al., 2013; Kretzschmar et al., 2015; Metzner et al., 2017; Niefind and Dimigen, 2016), with only a few studies addressing this issue in natural reading paradigms (Degno et al., 2018; Dimigen et al., 2011; Henderson et al., 2013; Kretzschmar et al., 2015; Metzner et al., 2017).

There may be several reasons why this is the case, but one of them is certainly the fact

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[3] Note however, that they recorded the eye movements via electrooculography (EOG; electrodes, placed below and to the left/right of the eye), to track blinks and saccadic movements, respectively.

[4] As recorded not only from the EOG electrodes, but rather in its full complexity, as tracked via eye trackers.

that simultaneous recording of EEG and eye movements presents a range of challenges, which become even greater when natural reading task enters the stage. As mentioned above, reading in its natural form presents a complex combination of a series of different eye movements. The most obvious challenge a natural reading paradigm has to face is thus the contamination of the EEG signal by eye movements (particularly saccades), resulting in noisy EEG data. In typical EEG (ERP) studies, the problem of contamination of the EEG signal through oculomotor artifacts is avoided by adopting the rapid serial visual presentation (RSVP) paradigms (e.g., Duffy et al., 1989; Morris and Folk, 1998). Here, words of a larger linguistic unit (typically a sentence) are presented one at a time, with a fixed and predetermined presentation duration which prevents the readers to take as long as needed to freely explore the word—and thus preventing excessive saccadic eye movements. Additionally, individual words typically appear in the middle of the screen, while participants are not only instructed to fixate their gaze to the position where the word will appear, but also to avoid blinking while the word is presented.

Needless to say, these paradigms substantially differ from human's natural, everyday experience of reading, in which we are given the opportunity to fixate each word for as long as we want and need to, to skip some words, to regress back to the text and to reread any parts of the text that we might need to in order to properly comprehend the presented reading material. However, is it possible to accomplish both, presenting a paradigm that would allow natural reading, while also obtaining EEG signal that is relatively free of the oculomotor artifacts?

The early coregistration studies dealt with this issue by limiting the data analysis to the less contaminated electrodes (e.g., Kretzschmar et al., 2009)[5]. But while this approach successfully avoids the problem of oculomotor artifacts in the neural data, it also leads to substantial data loss. In the recent years, however, several other methods for overcoming

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[5] Note, however, that while this study includes word recognition, the used paradigm does not include natural reading.

the problem of ocular artifacts in a free-viewing experimental setups have been developed (Dimigen et al., 2011). One such method is an eye tracker-supported Independent Component Analysis (ICA) (Plöchl et al., 2012). By itself, ICA is a blind source decomposition algorithm which enables a separation of statistically independent sources from multichannel data (e.g., Plöchl et al., 2012). It is widely accepted as an effective method for separating ocular artifacts from the EEG signal originating from neuronal sources (e.g., Hoffmann and Falkenstein, 2008; Jung et al., 2000; Plöchl et al., 2012), and frequently applied in many ERP studies. In eye tracker-supported ICA, however, the eye-artifact related ICA components are identified via the information, provided by the eye tracker, leading to a more reliable, objective and automated manner of component identification. After these artifacts are successfully identified, they can be either completely removed or substantially reduced, without affecting the remaining EEG signal (Plöchl et al., 2012).

But ocular artifacts are not the only challenge of the simultaneous recording of the EEG and eye tracking during normal reading. Another issue namely arises from the overlapping neural responses from subsequent events, such as, e.g., the overlap between the potentials elicited by successive fixations (Dimigen et al., 2011), which are an inevitable part of natural reading. Here again, RSVP paradigms avoid this problem (though not completely), as they introduce fixed and predetermined stimulus presentation duration, which is typically long enough to avoid the possible neural overlaps. In natural reading, however, words are typically fixated in a very rapid succession, with the interfixation intervals around 250ms (Dimigen et al., 2011)—which is substantially faster than the stimulus-onset asynchrony (SOA) in a typical RSVP paradigm. Thus, late components from the previous fixation *n-1* overlap with the early components from the current fixation *n*. This problem has been largely ignored by early FRP studies, as well as also by most of the ERP/RSVP studies, which might, despite the ability to control the SOA, still experience overlapping activity, e.g., from the button presses and stimulus onsets (Dimigen et al., 2011). However, the increased interest in shifting towards more natural reading paradigms, resulted also in increased interest in shifting the EEG analysis away from the simple averaging techniques, which cannot deal with this issue, towards the approaches that more successfully address this problem (Ehinger and Dimigen, 2018).

In the past years, several regression-based approaches have been introduced (e.g., Amsel, 2011; Frömer et al., 2018; Smith and Kutas, 2015a,b), which can successfully separate the overlapping potentials. These so-called deconvolution techniques handle the obtained EEG signal as a linear mixture of neuronal responses to different experimental events, which occur at different latencies. The latter are then used in order to isolate the neural response by tracing it back to its respective event (Ehinger and Dimigen, 2018). Applying these techniques to the actual EEG data is of course far from trivial. However, a very-recently released MATLAB toolbox *unfold* (Ehinger and Dimigen, 2018) integrates several different methods which are necessary for a successful deconvolution. As such it greatly facilitates the usage of the advanced deconvolution models, and opens up new possibilities for studying the neural responses in natural reading paradigms.

ERP signatures of language processing

Despite the existence of methods which overcoming difficulties of studying neural correlates during natural reading, EEG studies with natural reading paradigms are scarce at this point. Most of our current understanding of neural correlates of reading and, more general, of language processing is thus based on ERP/RSVP studies. These have importantly advanced our knowledge of language processing, particularly regarding semantic and morphological processing (e.g., Friederici et al., 1993; Kutas and Hillyard, 1980, 1984).

The rationale behind this approach is that the brain response to the target stimulus, compared to the control stimulus, reflects processes which are related to the semantic expectation and/or syntactic rule in question. This is most commonly established through the usage of the violations (e.g., Balconi and Pozzoli, 2005; Hagoort, 2003; Schacht et al., 2014; Van Petten et al., 1997)—the presented sentences violate either the morphological rule (e.g., *The old man eats an apples*.*) or semantic expectation (e.g., *The old man eats a sock*.*). The brain signatures of the processing in question are than extracted from the sentence with the violation, in comparison to the sentence without such violation (e.g., *The old man eats an apple.*), which serves as a baseline.

The ERP signatures, typically reported in respect to language processing are: (1) **the early left anterior negativity (ELAN)**, which peaks at around 200ms, with left-anterior distribution, in response to automatic early syntactic processes (e.g., Friederici, 1995, 2002; Friederici et al., 1993; Friederici and Weissenborn, 2007; Hahne and Friederici, 1999; Steinhauer and Drury, 2012); (2) **the left anterior negativity (LAN)**, which peaks at around 400ms, with left-anterior distribution, in response to morphosyntactic violations such as grammatical agreement violations, tense- and case-marking violations (e.g., Barber and Carreiras, 2005; Friederici, 1995, 2002; Molinaro et al., 2011); (3) **the N400**, a negative-going deflection, which peaks at around 400ms, with centro-posterior distribution, in response to lexical-semantic violations and anomalies (e.g., Federmeier, 2007; Hagoort, 2003; Kutas and Federmeier, 2000, 2011; Traxler and Gernsbacher, 2011); and (4) **the P600**, a positive-going deflection, which peaks around 600ms, with posterior distribution, in response to various violations of syntactic and morphosyntactic features, thematic-rule structure violations, temporary ambiguities, semantic anomalies, and long-distance dependencies (e.g., Carreiras, 2004; Friederici et al., 1993; Molinaro et al., 2011).

At this point, these well described ERP signatures are the starting point for the existing coregistration studies, which describe the observed FRPs in comparison to the specific ERPs.

Typically, these studies report FRPs, whose topographies and characteristics resemble the ERPs (Dimigen et al., 2011; Kretzschmar et al., 2015)—indicating that currently available methodology can successfully overcome the aforementioned problems. However, coregistration studies of natural reading suggest that in certain aspects the observed brain signatures importantly differ from the ones, observed in ERP/RSVP studies. Such difference is, e.g., their onset latency—in natural reading, the specific brain signatures seem to have an earlier onset (Dimigen et al., 2011; Kretzschmar et al., 2015; Metzner et al., 2017). These findings indicate that we cannot blindly assume that the ERP/RSVP findings would smoothly transfer to the actual, natural reading process, and speak up to the importance of conducting more EEG studies with natural reading paradigms, which would offer a fresh view on the phenomena observed in RSVP studies.

With our last study, presented in this thesis, we are hoping to contribute to this slowly growing body of literature and to shed new light onto the neural correlates of semantic and morphological priming in natural reading.

1.3 Slovenian language

So far, we have introduced the rationale that had led us to ask ourselves different research questions addressed in three largely independent studies. Yet, all three studies share a very important aspect, which enabled us to present novel paradigms and to address previously unaddressed questions—they are all designed on peculiarities of the Slovenian language.

The Slovenian language belongs to the family of Slavic languages, which are known for richness of their morphological systems (e.g., Reid and Marslen-Wilson, 2000). In Slovenian, almost every word is subject to inflection, which can be either conjugation (for verbs) or declension (for nouns, adjectives, pronouns, and numerals). As anyone who learned Slovenian as a foreign language would surely confirm, this results in a very complex inflectional system. Thus, we will avoid diving into all its details, and will rather focus solely on the properties we based our research on. Here, we offer a basic and slightly simplified description of the Slovenian noun declension.

Nouns in Slovenian exist within the inflectional system, consisting out of six different cases. In addition, noun's affixes do not only depend on their case, but also on their gender (i.e., feminine, masculine, and neutral) and number (i.e., singular, dual, and plural), resulting in specific affixes for the different combinations of the three. A single noun (e.g., *banka*, 'a bank'), can thus appear with a range of different affixes (e.g., feminine noun *banka*, 'a bank', in dative singular, dual, and plural, respectively: *bank-i*, *bank-ama*, *bank-am*). Despite the fact that not all affixes are distinct (e.g., genitive affixes are the same regardless of whether the noun is in dual or plural (e.g., *bank-∅*; but this declension still varies across genders), this kind of declension system results in very rich range of affixes, which we made use of in all three studies, presented in this work.

Another important property of nouns in Slovenian language is the fact that since the affixes carry all necessary information about the gender, number, and case, there are no determiners that would precede the noun (such as in, e.g., English). We made use of this property in our second and third experiment, in which we address the question of semantic and morphological priming in natural sentence reading—which could not have been done in other languages, where the determiner would cue the reader on the case and number before the noun itself would be processed (e.g., in an English sentence such as *The old man eats an apple*, the determiner 'an' cues the reader on the upcoming singular noun).

Additionally, the usage of the largely underinvestigated language allowed us to address another important issue—language diversity (e.g., Frost, 2012). Namely, with work presented here, we also hope to speak up to the importance of addressing research questions in a variety of the world's many languages, rather than focusing solely on the most well-established languages. In order to make assumptions about word identification and reading processes, one should namely consider the question of whether the previously observed and reported effects are a results of language processing in general, or rather result from idiosyncratic properties of specific language (Reid and Marslen-Wilson, 2000). In order to do so, more studies, conducted in different languages are needed—slowly, these kind of studies are emerging, and there is already a fair amount of research conducted in several 'less popular' languages, such as e.g., Czech (e.g., Smolik, 2010), Russian (e.g., VanWagenen and Pertsova, 2014), Arabic (e.g., Boudelaa and Marslen-Wilson, 2004).

2

Morphological priming of inflectional suffixes[1]

2.1 Introduction

It is now widely accepted that morphologically complex words (words that are made up of smaller meaning–bearing units, such as *kind-ness*, *move-ment* or *basket-ball*) are processed through their constituent morphemes during visual word recognition (e.g., Amenta and Crepaldi, 2012; Bradley, 1979; Rastle, 2011; Rastle et al., 2000; Taft and Forster, 1976). This was primarily established through the priming paradigm, in which the relationship between two words in the mental lexicon is assessed by measuring how the presentation of one (the prime) influences the response to the other (the target) (e.g., Boudewyn et al., 2012; Camblin et al., 2007; Sebastiani et al., 2015). There is now substantial evidence showing that facilitation emerges when primes and targets are morphologically related, over and above their orthographic and semantic similarity (e.g., Feldman, 2000; Longtin et al., 2003; Rastle et al., 2004).

The vast majority of this priming literature has focused on *stem* priming, showing that

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[1] All materials, data and analysis scripts for this study are available to the reader here.

stem words, e.g., *kind*, are identified more quickly when preceded by a morphological relative, e.g., *kindness*, compared to an unrelated word, e.g., *boldness*. The key in this paradigm is that primes and targets share their stem, hence the name.

What happens when primes and targets share an affix instead has been somewhat more controversial, particularly when suffixes are considered (e.g., *kindness–vagueness*). In a masked priming study in Spanish, Duñabeitia et al. (2008) observed clear effects of suffix priming, regardless of whether the primes were: (i) suffixes in isolation (e.g., *dad–IGUALDAD*); (ii) suffixes inserted into symbol strings (e.g., *%%%%dad–IGUALDAD*); or (iii) real words (e.g., *brevedad–IGUALDAD*). Facilitation was consistently larger than that observed when the prime–target pairs shared non-morphological letter endings (e.g., *men–CERTAMEN*), thus suggesting a genuine morphological nature for this effect.

Results from a masked priming study carried out in French are less encouraging, though. Giraudo and Grainger (2003) presented their participants with prime words that shared with their targets either a valid suffix (e.g., *veston*, little jacket, and *CHATON*, little cat) or a pseudosuffix (e.g., *béret*, beret, and *MURET*, little wall). These conditions were tested with an unrelated baseline (e.g., *crabe–MURET*), and gave rise to no consistent facilitation—out of four experiments, some (statistically weak) priming only emerged for transparent suffixed words that were also orthographically similar to the targets, and for which the morphological boundary overlapped with the syllabic one.

The use of word primes in these experiments has likely triggered lexical competition (e.g., Davis and Lupker, 2006), which may have interacted with the morphological dynamics making it difficult to assess suffix priming per se. This issue does not affect the experiments in Crepaldi et al. (2016), where nonword primes were used. These authors observed clear effects of suffix priming when targets were preceded by nonword primes with a shared suffix (eg., *sheeter–TEACHER*), compared to when they were preceded by a nonword (i) with a different suffix (*shetal-TEACHER*), or (ii) with an unrelated non-morphological ending (e.g., *sheetub–TEACHER*). Additionally, no effect was observed in a fully non-morphological set of conditions with the same degree of orthographic overlap—*apparel* was identified as quickly after *colourel*, *colouric* or *colourut*, ruling out the possibility that the observed effect could be assigned to similarity in form. Overall, these data provide strong support for the existence of suffix priming.

Note that establishing suffix priming is of some theoretical importance, given that theories of visual word identification place different emphasis on the relative role of stems and affixes (Grainger and Beyersmann, 2017). If the two types of morphemes yield priming similarly, then it is likely that they are similarly represented in the lexical identification system. This would also be notable from an information theory point of view; the distribution of stems and affixes in the language is in fact very different. While affixes are few, and tend to be highly frequent, lexical stems are many, and generally of lower frequency. Thus, stems are more informative on word identity—knowing that a word contains, e.g., *-ment* leaves the reader with lots of viable options (that is, with high uncertainty), while knowing that it contains, e.g., *flavour* constrains the cohort of possible candidates down to a handful of alternatives. That the visual word identification system is insensitive to this informational asymmetry would be very interesting, and possibly revealing on its computational architecture. On the other hand, suffixes' higher frequency may make them easier to identify quickly, which may give an important headstart to the visual identification process.

The studies described above all assess *derivational* suffixes, which leaves open another interesting question: what happens with *inflectional* suffixes? There are several reasons to believe that these latter may have a very different role in the lexical system. Linguists draw a strong dichotomy between inflection and derivation (e.g., Haspelmath, 2010): (i) inflection never indicates the change of grammatical category (e.g., dog-dogs) while derivation always does (e.g., dark-darkness), (ii) inflection is typically more semantically transparent (relationship between dog-dogs is identical to the relationship between car-cars), while derivation is more idiosyncratic (e.g., ‘gardener’ is a person who takes care of the garden, while ‘a juicer’ is a kitchen appliance that makes juice; e.g., Crepaldi et al. (2010)), and (iii) inflection never introduces a new meaning to their base morphemes, while derivation can (e.g., person-personal).

Some information about inflectional priming comes from a group of studies based on Slavic languages, which are aptly inflectionally rich. Reid and Marslen-Wilson (2000) report on a cross-modal priming experiment carried out in Polish. They considered four affix conditions, in which all the primes were existing words: (i) verbs with shared aspectual prefix (***s****korzystać*, ‘to benefit’, perfective–stracily, ‘they lost’, perfective), (ii) verbs with shared derivational prefix (***na****grzać*, ‘to heat up’, perfective–nakroila, ‘to cut’, perfective), (iii) nouns with shared diminutive suffix (*kot****ek***, ‘a little cat’–(*ogrod****ek***, ‘a little garden’), and (iv) nouns with shared derivational suffix (*kuch****arz***, ‘a cook’–(*pillk****arz***, ‘a footballer’). Priming was only significant when the data for all affixal conditions were considered together as a group; inflectional suffixes alone did not yield any facilitation.

A more recent study was carried out in Russian (VanWagenen and Pertsova, 2014). Primes were all existing words in this language, either nouns or verbs, which either shared their inflectional suffix with the target (e.g., vʲɪrnʲot (return-3p.sg.pres.)–trʲəsʲot (shake-3.p.sg.pres), or only overlapped with it orthographically and phonologically (e.g., patːçot (count (n)–trʲəsʲot (shake-3.p.sg.pres). However, only verb primes were presented in isolation, and are thus informative to our purposes. These stimuli did yield significant facilitation, contrary to the nominal primes, which were presented together with a determiner—whether this represents a genuine grammatical class effect, or is rather a by–product of the different contexts where the primes were presented, it is difficult to establish.

Another group of studies that addressed inflectional priming were carried out on Semitic languages (e.g., Arabic, Boudelaa and Marslen-Wilson (2004), and Hebrew, Deutsch et al. (1998); Frost et al. (1997)), where inflections take the form of word patterns that are intertwined to lexical stems (e.g., a morpheme -drx (conveying the meaning of 'stepping') is inserted in a nominal pattern *mi_ _ a_ a* (where the dashed lines indicate the places where the morpheme's consonants are to be inserted), resulting in a noun *midraxa*, 'pavement' (Deutsch et al., 1998)). These studies also yielded mixed results. The Arabic data revealed priming with one type of inflectional morpheme (i.e., consonant–vowel pattern), but not with another (i.e., vocalic melody), despite the fact that they both encode inflectional information (Boudelaa and Marslen-Wilson, 2004). On the other hand, evidence from Hebrew suggested root priming in nouns and verbs, while word–pattern priming only emerged with the latter grammatical class (Deutsch et al., 1998; Frost et al., 1997). This would be in line with the data provided in Russian by VanWagenen and Pertsova (2014).

Overall, the existing evidence is clearly inconclusive; there are reports of inflectional suffix priming, but this effect seems to be far from consistent. As illustrated above, however, the experiments carried out so far are very diverse—to mention just a few factors, scholars presented primes in different contexts, investigated languages with very different morphologies, and used different prime presentation times and modalities. Although diversity is clearly important in psycholinguistics, on this specific instance it makes it difficult (impossible?) to establish whether inflectional priming is truly weak or nonexistent, or rather the inconsistent pattern of results emerges right from this diversity. We thus felt that a novel, more systematic investigation of inflectional suffix priming was in order.

The two experiments we present here have a few key features. First, primes were kept outside of the participants' awareness, thus making them blind to our experimental manipulation; this grants us protection from any effect of meta–cognitive strategy that participants may put in place. Second, inflectional priming is compared directly with stem priming in a within–target design; this would speak to the potential stem–suffix asymmetry that we discussed above. Third, we used nonwords as primes, thus allowing a better control of the experimental material and excluding lexical competition dynamics that may interfere with the morphological effects we're most interested in[2].

The experiments were carried out in Slovenian, taking advantage of its very rich inflectional system. Slovenian nouns have six cases, three genders and three grammatical numbers, all of which are combined into one inflectional suffix (e.g., *brat**a***, brother, singular, accusative; *brat**oma***, brother, dual, dative). This granted us a considerable amount of flexibility in the construction of our stimuli, which we exploited to guarantee a well–controlled, within–target design. In Experiment 1, we focused on assessing stem and suffix priming, each against their ideal control conditions, i.e., ***halj**ov*–***HALJ**AM* vs. ***jaht**ov*–***HALJ**AM*, and *mest**am***–*HALJ**AM*** vs. *mest**ov***–*HALJ**AM***. In Experiment 2, we varied the sharing of stem and suffix parametrically—the same target *HALJAM* was primed by ***haljam*** itself, stem+suffix+, ***halj**ov*, stem+suffix−, *mest**am***, stem−suffix+, and *jahtov*, stem−suffix−. This generated a fully crossed, 2×2 design that allowed us to: (i) assess the contribution of a shared stem and a shared suffix independently, within the same model; and (ii) gauge the possible interaction between the sharing of the two morphemes.

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[2] There is one exception in Experiment 2, where we did use existing words as primes in one condition. However, these word primes are actually repetition primes, which still avoids triggering lexical competition dynamics. We take up this issue more fully below.

2.2 Experiment 1

2.2.1 Methods

Participants

Sixty native Slovenian speakers (F=41) took part in the study. Their mean age and education was 30.8 (range=20-60) and 15.18 years (range=12-18), respectively. They all grew up in a monolingual environment and had normal or corrected-to-normal vision. They all signed an informed consent form to take part into the study, and received 2 Euros in compensation.

Materials

The stimulus set was based on 40 Slovenian nouns to be used as targets. These were all feminine nouns inflected in the dative plural case[3] (e.g., *sestram*, (to the) sisters). Each target word was paired with four different nonword primes, which were all built as non–existing combinations of an existing stem and an existing affix (corresponding examples in English would be *builded*, or *drawed*). There were no phonological/orthographic modifications in either the stem or the suffix in all primes. In the suffix–related condition, the prime and the target shared the same suffix (e.g., *okn**am**–MAM**AM***, windows–MOTHERS). In suffix–control, the prime was made up of the same stem, now paired with a different suffix (e.g., *okn**ov**–MAMAM*). The stem priming conditions were built similarly; related primes shared their stem with the target word (***mam**ov–**MAM**AM*), whereas their controls featured a different stem, attached to the same suffix ***čaj**ov–**MAM**AM*, teas–MOTHERS. An overview of the four experimental conditions is offered in Table 2.1).

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[3] This particular inflection was chosen, as it results in a two-letter suffix, which is unambiguously assigned to this gender-case combination. Other combinations result either in one-letter suffix, or are ambiguous when a noun is presented in isolation (ie., the same suffix belongs to more than one nominal inflection).

Table 2.1: Prime–target pairs across the four experimental conditions in Experiment 1.

Condition	Prime	Target word
Suffix related	okn**am**	MAM**AM**
Suffix control	okn**ov**	MAM**AM**
Stem related	**mam**ov	**MAM**AM
Stem control	**čaj**ov	**MAM**AM

The within–target design guarantees perfect matching across conditions on this front; further care was taken to also ensure prime comparability. Overall, stem and suffix length were matched pairwise between related and control primes; stem frequency was also nicely matched (Table 2.2). Prime–target orthographic overlap was calculated through the computer program `MatchCalculator` (Davis, 2006), based on orthographic spatial coding (Davis, 2010). Because stems are generally longer, stem primes were unavoidably more similar to their targets than suffix primes; therefore, we adjusted orthographic overlap in the control conditions so that the difference between related and control primes was the same for stems ($.62 - .27 = .35$) and suffixes ($.42 - .13 = .29$).

Table 2.2: Stimuli characteristics across conditions. Stem-, and suffix-length, reported with medians and IQRs; log frequency, and orthographic overlap, reported with means and SDs.

	Target word	Suffix prime	Suffix control	Stem prime	Stem control
Stem length	4.0 (2)	4.0 (2)	4.0 (1.25)	4.0 (2)	4.0 (2)
Suffix length	2.0 (0)	2.0 (0)	2.0 (0)	2.0 (0)	2.0 (0)
Stem frequency	1.46 (.65)	1.29 (.81)	1.29 (.81)	1.46 (.65)	.97 (.82)
Orthographic overlap		0.42 (0.09)	0.13 (0.08)	0.62 (0.04)	0.27 (0.12)

Our stimulus set also included 40 nonword–target trials, which required a NO response from the participants. Targets in these trials were built in four groups of 10 items: existent stem+existent suffix (e.g., *knjigta*), existent stem+non-existent suffix (e.g., *vodla*), non-existing stem+existing suffix (e.g., *rohom*), and non-existing stem+non-existing suffix (e.g., *gamdem*). The last three groups guarantee that not all target stimuli were combinations of existent morphemes, which was critical to prevent participants from engaging in a mere morphological check, rather than a lexical decision task. Each nonword target was paired with a nonword prime based on the same design described above for the word–target, experimental trials; this guarantees that the prime structure was non-informative as to the lexicality of the target.

Procedure

Participants were presented with a lexical decision task, in which they were instructed to press one of two buttons as quickly as possible according to whether the presented letter string was an existent Slovenian word. They were informed that the letter string would be preceded by a string of hash marks, but they were not informed about the presence of the prime words. They sat around 56 cm from the computer screen where the stimuli were displayed. A Cedrus response box was used to collect their responses, on which the YES response button was always controlled by the participant's dominant hand. At the beginning of the experiment, participants underwent a short practice session with 10 trials, to properly familiarize themselves with the task before the onset of the actual experiment.

The trial timeline was as follows. A fixation cross appeared in the middle of the screen for 400ms, followed by a visual mask (######) for 500ms. Afterwards, the prime was presented in lowercase for 36ms, followed by the uppercase target word, which remained on the screen for 2s. Participants had up to 2s to give their response, before the new trial began.

In order to avoid repetition effects, each participant was presented with each target in only one out of the four experimental conditions, with a Latin Square design rotation.

Data Analysis

Response times (RT) in correct trials were analyzed through linear mixed models (LMMs) using `R` (R Development Core Team, 2008), `Rstudio` (RStudioTeam, 2016), and its packages `lmerTest` (Kuznetsova et al., 2017) and `Effects` (Fox and Hong, 2009). RT were were inverse-transformed in order to achieve symmetrically distributed residuals, and were modelled as a function of prime relatedness (related vs. control) and priming morpheme (suffix vs. stem), with subjects and target words as crossed random intercepts. Parameters were checked for their dependence on outliers following Baayen (2008)—models were re–run after excluding data points whose standardised residuals were larger than 2.5 in absolute value.

2.2.2 Results

We excluded from the analysis one participant who performed at chance level on nonword trials, and one target word that elicited an overall accuracy below 70%. The mean overall response time and accuracy are 715ms and 94%, respectively. The descriptive statistics by condition are offered in Table 2.3.

Table 2.3: Mean (SD) and median (IQR) reaction time, reported in ms, and accuracy (SD), reported in %, across the four conditions. Statistics are based on unaggregated data.

	Mean RT	Median RT	Accuracy
Stem control	709.84 (209.80)	662 (229.00)	95 (0.21)
Stem priming	687.94 (205.76)	639 (211.50)	95 (0.21)
Suffix control	738.17 (227.80)	690 (265.50)	94 (0.23)
Suffix priming	724.37 (217.38)	672 (253.75)	93 (0.25)

The analysis suggests a main effect of primes relatedness, $F(1, 2110.6) = 12.28$, $p < .001$, a main effect of priming morpheme, $F(1, 2111.0) = 32.11$, $p < .001$, and no interaction between the two factors, $F(1, 2110.2) = 2.22$, $p = .14$. The model parameters show that sharing a stem yields solid priming, $t(2110.8) = -3.55$, $p < .001$, and that suffix priming doesn't differ from stem facilitation, $t(2111.2) = 1.49$, $p = .14$. Importantly, though, when the reference level for *priming morpheme* was set to *suffix*, so that the model parameters inform directly on suffix priming, this effect was barely significant in the outliers–free model, $t(2070.2) = -2.03$, $p = .04$, and not significant in the full model, $t(2111.0) = -1.41$, $p = .16$. Based on these models, stem priming is estimated to be 24ms, while suffix priming amounts to 11ms. Figure 2.1 presents the estimated effects based on these models.

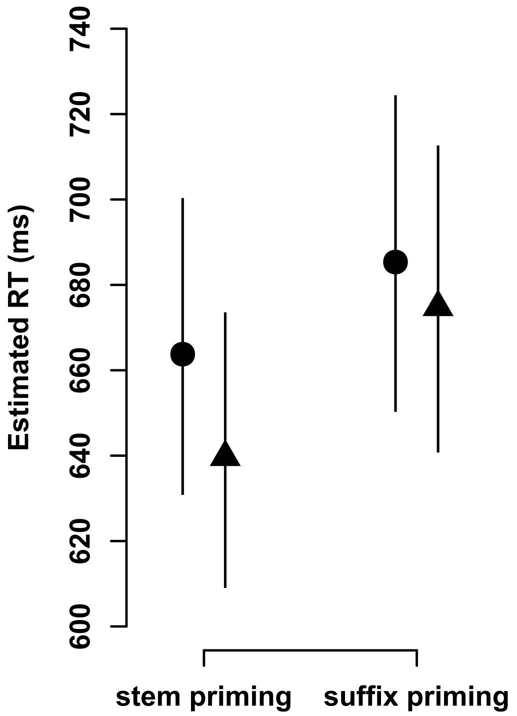

Fig. 2.1: Estimated RT(ms), plotted per priming type (stem and suffix), for control and prime condition. The error bars represent the CI of 95%. Note: ●/▲, control condition/priming condition.

2.2.3 Discussion

The results of Experiment 1 suggest solid morphological priming when inflected nouns (e.g., *MAMAM*, (to the) mothers) are primed by morphologically complex nonwords sharing the same stem (e.g., *mamov*), compared to when they are primed with an unrelated nonword (e.g., *čajov*).

Data are less clear on inflectional suffix priming. On the one hand, there is no significant interaction between prime relatedness and priming morpheme; this would suggest that suffix priming isn't different from stem priming. On the other hand though, the model estimates reveal a numerically smaller effect for suffixes than for stems (11ms vs. 24ms); and, perhaps more importantly, when the reference level for *priming morpheme* is set to assess suffix priming directly, statistics are rather weak—the effect is only significant (and barely so) when the model is clean of outliers.

Experiment 1 was designed to contrast each related prime with its closest possible control (e.g., ***halj**ov*–***HALJ**AM* vs. ***jaht**ov*–***HALJ**AM*). Essentially, everything remained the same in related and control primes, except that the priming morpheme was changed with a matched, target–unrelated one. Experiment 2 is another attempt at assessing stem and suffix priming, this time using a fully factorial design where each target word (e.g., *LISAM*) is preceded by a prime with: (i) the same stem and the same suffix, making up a repetition prime; (ii) the same stem and a different suffix, e.g., ***lis**ov*; (iii) a different stem and the same suffix, e.g., *gib**am***; and (iv) a different stem and a different suffix, e.g., *berov*. This fully factorial design allows us to assess the contribution of a shared stem and a shared suffix independently; this may be particularly useful to shed light on the somewhat unclear results on suffix priming that emerged in Experiment 1. Moreover, it permits us to check for an interaction—would stem/suffix priming be stronger/weaker when targets and primes also share their other morpheme? Of course, such a design forced us into using word primes in one of the four conditions; these word primes, however, would be the target words themselves, which keeps us clean of effects of lexical competition and/or complex lexical dynamics that may obscure the purely morphological effects.

2.3 Experiment 2

2.3.1 Methods

Participants

Sixty-two native Slovenian speakers (F=46) participated in the Experiment 2, none of whom took part in the Experiment 1. Their mean age and education was 24.6 (range=19–42) and 14.9 years (range=12-20), respectively. They all grew up in a monolingual environment and had normal or corrected-to-normal vision. They all granted their informed consent to take part into the study before the beginning of the experiment, and received 2 Euros in exchange for their time.

Materials, procedure and data analysis

Identically to Experiment 1, the stimulus set was based on 40 Slovenian word targets, which were also used in the previous study. Each target (e.g., MOČEM) was paired with four different primes, following a crossed, 2 × 2 design: (i) same stem and same suffix, making up a repetition prime (e.g., **močem**); (ii) same stem and different suffix (e.g., **moč**ov); (iii) different stem and same suffix (e.g., dom**em**); and (iv) different stem and different suffix (e.g., župov).

The statistics of this stimulus set are reported in Table 2.4. The presence of repetition primes, the fully factorial design and, again, the fact that stems are generally longer than suffixes create an imbalance in prime–target orthographic overlap—if one averages stem–related vs. non–stem–related primes, and suffix–related vs. non–suffix–related primes, the former comparison displays a larger difference in orthographic overlap than the latter ($.81 - .31 = .50$ and $.71 - .41 = .30$, respectively). This means that stem priming might be unduly inflated by prime–target form similarity as compared to suffix priming. We will take care of this confound statistically (see below).

Table 2.4: Stimuli characteristics across conditions. Stem-, and suffix-length, reported with medians and IQRs; log frequency, and orthographic overlap, reported with means and SDs.

	Target word	Suffix prime	Stem prime	Repetition prime	Control
Stem length	4.0 (2)	4.0 (2)	4.0 (2)	4.0 (2)	4.0 (2)
Suffix length	2.0 (0)	2.0 (0)	2.0 (0)	2.0 (0)	2.0 (0)
Stem frequency	1.46 (.65)	1.30 (.81)	1.46 (.65)	1.46 (.65)	1.25 (.73)
Orthographic overlap		0.42 (.09)	.62 (.05)	1.0 (0)	.19 (.10)

All other aspects of the Experiment 2 were kept identical to Experiment 1, including the number and structure of nonword trials, the procedure, the trial timeline and the data analysis approach.

2.3.2 Results

No participant or target word met the exclusion criteria; thus, all datapoints were retained into the analyses. The mean overall response time and accuracy in this experiment were 714ms and 94%, respectively; quite nicely, these figures are very similar to those observed in Experiment 1. The descriptive statistics by condition are offered in Table 2.5.

The model suggests solid stem priming, $F(1, 2222.6) = 48.44$, $p < .001$, but no suffix priming, $F(1, 2223.6) = .20$, $p = .65$, nor any interaction between the two, $F(1, 2224.0) = 2.01$, $p = .16$. The estimated effect size is 33ms for sharing a stem, and 3ms for sharing an inflectional suffix. Figure 2.2 presents the model–based estimates for each design cell.

Table 2.5: Mean (SD) and median (IQR) reaction time, reported in ms, and accuracy (SD), reported in %, across the four conditions of experiment 2. Statistics are based on unaggregated data.

	Mean RT	Median RT	Accuracy
Stem priming	699.95 (223.88)	647 (238)	96 (.19)
Suffix priming	732.29 (217.56)	680 (233)	95 (.20)
Repetition priming	693.66 (221.40)	645 (238)	95 (.21)
Control	730.80 (243.23)	672 (239)	93 (.25)

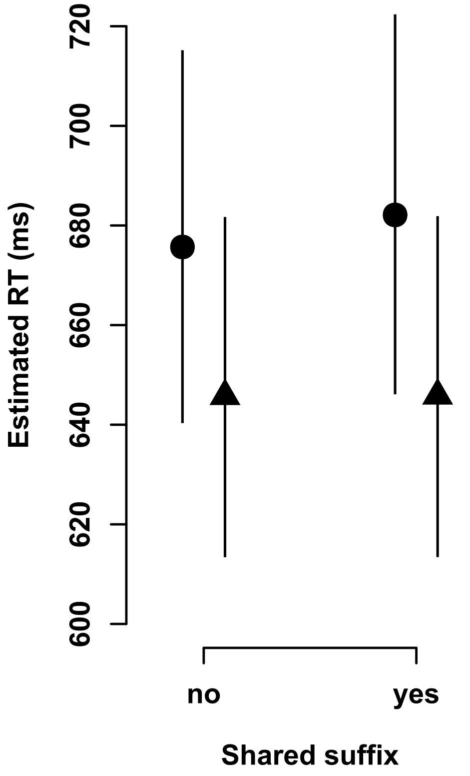

Fig. 2.2: Estimated RT(ms), plotted per shared suffix (no/yes), for shared stem and unshared stem. The error bars represent the CI of 95%. Note: ●/▲, stem not shared / stem shared condition.

As we discussed above, the difference in prime–target overlap between related and control primes is larger for stem than for suffix priming in this experiment (see Table 2.4). It is logically possible, then, that stem priming has emerged as a side effect of form similarity;

perhaps primes and targets were just similar enough orthographically when they shared a stem, but not when they shared a suffix. In order to exclude this possibility, we checked that stem priming remains significant in a model that also includes orthographic similarity as a covariate; this was indeed the case, $F(1, 2233.1) = 9.47$, $p = .002$. We also checked that sharing a stem still brings significant time savings on the residuals of a model that accounts for orthographic overlap, that is, on that part of the response times that orthographic similarity can't account for; and again, this was indeed the case, $t(61) = -1.68$, $p = .05$[4]. So, it really seems that the nature of the stem priming effect is morphological in nature.

2.3.3 Discussion

In line with much of the previous literature (e.g. Forster and Azuma, 2000; Marslen-Wilson et al., 1994; Rastle et al., 2000, 2004), Experiment 2 fully confirms the solid stem priming effect observed in Experiment 1. It also shows that this effect is morphological in nature, and not entirely accountable in terms of prime–target orthographic overlap.

Experiment 2 brings no evidence, instead, for savings related to primes and targets sharing their inflectional affix. This may elucidate the somewhat unclear results that emerged in Experiment 1, where suffix priming was on the verge of statistical significance, and nearly significantly different from stem priming. Statistics are fully unambiguous in this new experiment—while stem priming is very solid, there is virtually no evidence for any suffix priming.

Quite interestingly, there is no evidence for any interaction between stem and suffix priming. Namely, a shared suffix did not add any further facilitation when the stem was also shared between the prime and the target; and vice versa, a shared stem did not enhance suffix priming. This result also confirms that the lexical status of the primes in the repetition priming condition (stem+suffix+) did not influence the facilitation pattern, or otherwise we would

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[4] We carried out a simple t test here because the crossed random effects of participants and targets were already accounted for in the orthographic overlap model, which made unnecessary to use mixed models a second time.

registered a difference between repetition primes (which were real words) and stem+suffix-primes (which were not real words). Instead, the two types of primes yield very similar time savings.

2.4 General discussion

Building on one of the most well-established paradigms in single word visual identification, that is, masked priming, we investigated inflectional priming in Slovene, and compared it to stem priming. This latter effect emerged clearly, whereas, overall, our data do not seem to support inflectional suffix priming. We also observe that there is no interaction between sharing a stem and sharing an inflectional suffix; the overall priming effect seems to be best descried as the mere sum of an existent and solid stem priming, and a nonexistent (or at best, very weak) suffix priming.

Stem priming is already a very well established phenomenon (e.g., Amenta and Crepaldi, 2012; Feldman, 2000; Marslen-Wilson et al., 1994; Marslen-Wilson, 2007; Rastle et al., 2000; Stanners et al., 1979). However, we report it in a language that was previously unaddressed in this respect, and that differs in many aspects from the languages where most of the evidence on morphological priming was obtained, such as English, German or Spanish. Most notably, the Slovene noun inflectional system is way richer than any of these languages; stem priming does seem to hold smoothly irrespective of this factor. Slavic languages are in general understudied in the psycholinguistic literature (but see e.g., Filipovic Durdevic et al., 2009; Kostić, 1991; Milin et al., 2009, for notable exceptions); so these experiments also provide an important contribution towards a psycholinguistic knowledge that is more appropriately based on a diversity of languages (Frost, 2012; Reid and Marslen-Wilson, 2000).

Overall, our data seem to suggest no inflectional suffix priming—there is no reliable facilitation in the recognition of a complex word that is preceded by a morphologically structured nonword with the same inflectional suffix (*prst**am**–HALJ**AM***). Importantly, these results come from a paradigm and a language that arguably set the ideal stage for inflectional suffix priming to emerge. As mentioned above, nominal inflection is ubiquitous in Slovene, and also the result of a very complex system where three different numbers (singular, dual and plural), three different genders (masculine, feminine and neuter) and six different cases (nominative, genitive, dative, accusative, locative and instrumental) get blended in one inflectional suffix. Moreover, our target words were all suffixed—despite masked priming kept our experimental manipulation out of our participants' awareness, this feature should have, if anything, directed even more attention to inflections. Yet, no solid inflectional priming emerged.

This absence of inflectional suffix priming is particularly interesting. Previous research suggests that derivational suffixes do play an active role in the visual identification of complex words (e.g. Crepaldi et al., 2016; Duñabeitia et al., 2008). In the presence of further evidence that assigns a similar role to prefixes (e.g., Chateau et al., 2002; Dominguez et al., 2010; Giraudo and Grainger, 2003; Reid and Marslen-Wilson, 2000, 2003), one could assume that these findings can be just generalized to any kind of affix (Crepaldi et al., 2016). Here, however, we show that this might not be the case—inflectional suffixes do not seem to play a big role in complex word identification.

Of course, more research is in order here before holding this claim strong. The comparison between inflectional and derivational priming, for example, can only be made cross–linguistically at the moment. While linguistic diversity is of course fundamental, one can never exclude that some peculiarity of one language makes it more prone to derivational (rather than stem, or inflectional) priming, with no real general information that we can draw on the human visual word identification system in general. In this specific case, perhaps suffix priming—no matter whether inflectional or derivational—is generally more difficult to obtain in Slovene, and thus what we're seeing here is not really a derivation–inflection asymmetry, but a cross–linguistic difference between, e.g., English and Slovene. Some direct, within–language comparison between inflectional and derivational priming would be a nice complement to the present study. Also, we excluded that the pattern of results is entirely due to orthographic overlap via statistical analyses. We obviously believe that this is surely informative; and also, this was the only viable option in this study, because all Slovene nouns must be inflected, and it was thus impossible to test monomorphemic stimuli. However, some direct comparison between these latter and inflected words (something similar to the English examples *cat**ket**–BUC**KET*** vs. *cat**ing**–EAT**ING***) would further confirm the genuinely morphological nature of these effects.

While it may seem surprising that derivational suffixes would contribute to complex word processing, while inflectional suffixes would not, it is possible that the reason for this discrepancy lies in the nature of the information they carry. While inflectional suffixes only provide morpho–syntactic information, derivational suffixes typically carry lexical knowledge. For example, derivational suffixes determine grammatical class (*kind**ness***, *bitter**ness*** and *ill**ness*** are all nouns), while inflectional suffixes never do (a noun is a noun by virtue of its stem, no matter which inflectional affix that stem takes on each specific instance). From this perspective, derivational suffixes are more similar to stem morphemes, whose role in complex word processing is undisputed.

A different interpretation would point on the informational structure of stems and (particularly inflectional) suffixes frequency distribution. As anticipated in the Introduction, stems are more informative on lexical identity. Nearly all English nouns take an *-s* to form a plural, thus knowing that the word we're trying to identify contains that morpheme is virtually useless to constrain our lexical search—we'd be left with thousands of candidates. Knowing which stem we're looking at, instead, would typically leave us with a handful of candidate words. Perhaps the visual word identification system captures this informational asymmetry, and consequently focus on stems way more than on suffixes. Admittedly, derivational suffixes would be somewhat puzzling on this account. They generally carry more lexical information than inflectional suffixes (e.g., there are less words containing -*ness* than words containing -*ing* in English). Yet, they are also less informative than stems; therefore, it is not obvious that they should yield solid priming, which is what data seem to indicate. More generally, morpheme types as they are defined in theoretical linguistics would lose importance on this informational account; arguably, the lexical system would develop sensitivity to each individual morpheme informational value, making a general distinction between stem, inflectional and derivational morphemes rather irrelevant.

3

Semantic and morphological priming in natural sentence reading[1]

3.1 Introduction

Over the last decades, we have learned a great deal about visual word identification (e.g., Adelman et al., 2010; Forster and Veres, 1998; Marelli et al., 2015; Rastle et al., 2000; Xu and Taft, 2014). Our knowledge is so rich and articulated that it fostered the construction of fully–fledged computational models—our theories of visual word processing have reached a mechanistic level (e.g., Adelman, 2011; Coltheart et al., 2001; Davis, 2010; Perry et al., 2010). This knowledge, however, is very much focused on individual word identification, while our everyday life experience is dominated by text reading instead. This requires the visual identification system to deal with several words in a very short amount of time (~300 words per minute; Pelli et al., 2007)—the very detailed models described above remain agnostic as to this fundamental aspect of human reading.

From this perspective, models of eye movement are a particularly interesting case (Engbert

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[1] This chapter is also an independent paper (in submission). Paper preprint, all data and analysis scripts are available to the reader here.

et al., 2005; Reichle et al., 2006). By design, they have to deal with the identification of several individual words during sentence reading; that is, they face the problem of having the visual word identification system engaged with several words in very rapid succession (in serial models, such as in E–Z Reader), or even simultaneously (in parallel models, such as in SWIFT). How a unique visual word identification system would deal with this issue is not obvious. More generally, these models stay clear of the lexical dynamics described in models of single word identification; they typically treat this latter process as an unarticulated whole, of which they only estimate the duration/difficulty based on proxies such as word frequency or word predictability in a given sentence context.

Of course, there are exceptions to this general trend. In their *Glenmore* model, Reilly and Radach (2006) include letter–level dynamics, which may allow some contact between visual word identification theories and text reading. However, the authors themselves acknowledge that they were more interested into modelling target words for saccades rather than implementing realistic lexical dynamics. The very recently released *OB1–Reader*, instead, makes exactly this step, and aims at integrating what we know about individual word identification into a general account of text reading (Snell et al., 2018b). Here we follow very much in the same spirit, moving the focus from eye movements, which is the main target in *OB1–Reader*, to post–orthographic processing levels in lexical identification, and how these are affected by the engagement of the visual word identification system with multiple words in very rapid succession.

Our starting point is one of the most established phenomena in the individual word identification literature, namely, *priming*. It is extremely well demonstrated now that seeing a semantically (e.g., 'sell') or morphologically (e.g., 'dealer') related word makes it easier to then identify a given target (e.g., 'deal'; Feldman (2000); Forster et al. (1987); Grainger et al. (1991); Neely (1977); Rastle et al. (2000)). Exactly because the lexical system is bombarded with words in very rapid succession during sentence reading, lexical identification should be dominated by this kind of cross—word effects. Just as well as seeing 'nice' in the middle of a black screen would make it quicker to identify the word 'kind' in isolation, reading the former word should make it easier to then recognize the latter when they lie close within the same sentence. In other words, there should be extensive *cross—word priming* during sentence reading. This is the phenomenon we investigate in this paper, to start filling the gap between individual word identification and sentence reading.

Although from a rather different perspective, lexical dynamics during sentence reading were of course investigated in previous work. For example, a number of studies have addressed semantic priming in sentences, and yielded mixed results—while some have reported facilitation (e.g., Blank and Foss, 1978; Van Petten et al., 1997), others have found that lexical priming is easily overridden by message-level factors, such as discourse context and predictability (e.g., Duffy et al., 1989; Morris, 1994; Morris and Folk, 1998; Traxler et al., 2000). For example, Morris (1994) reported savings in the identification of a target word (e.g., 'moustache') from a related verb prime ('trimmed') in sentences like 'the gardener talked as the barber trimmed the moustache', but not in sentences with manipulated semantic relationship between the subject and the verb, like 'the gardener talked to the barber and trimmed the moustache', suggesting that the facilitation of target word identification depends on discourse context.

Morphological effects were also heavily studied in sentence reading (e.g., Barber and Carreiras, 2005; Kos et al., 2010; Kutas and Hillyard, 1980, 1984; Weber and Lavric, 2008). Most of this work, however, is rather difficult to interpret in terms of cross–word priming, given that it is based on morpho–syntactic violation paradigms (e.g., 'the old man eats an apple*s*').

Some morphological congruity effects in naturalistic material were indeed observed, which can be interpreted in terms of cross–word morphological priming. However, these experiments typically involved rather minimalistic environments such as word pairs (e.g., Goodman et al., 1981; Samar and Berent, 1986; West and Stanovich, 1988). For example, they report how the (dis)agreement between an adjective and its following noun (e.g., 'brutta casa' vs. *'brutto casa') influences the processing of the latter, where the introduced disagreement results in e.g., longer response time in word repetition tasks, compared to when noun agreement is not violated (Bates et al., 1996). It is far from clear whether this kind of effects would generalise to content word priming, similar to what is typically investigated in the individual word literature (e.g., dealer–deal, kindness–softness). Also, it is not established whether they would emerge in naturalistic, everyday life sentence reading—without this, we miss the bridge between single word identification and text reading that we are aiming at.

Eye tracking can help us out of the unnaturalistic paradigms that were adopted in previous studies, thus allowing us to assess cross–word priming under more natural reading conditions. In fact, priming may emerge as shorter fixations on words that were preceded by semantically or morphologically congruent words, while participants are simply asked to read sentences for comprehension. At the same time, eye tracking allows us to use the material that is typically adopted in the single word literature. For example, content words that are semantically and/or morphologically congruent are located close to each other in a sentence (e.g., '...forks and spoons...'), so that if the relevant information persists in the lexical system, we should observe savings in the identification time (that is, fixation durations) of the latter word. Quite conveniently, eye tracking would also allow us to estimate the time course of the eventual effects, through a comparison between earlier fixation measures (e.g., first–of–many fixation duration) and later eye movement metrics (e.g., gaze duration). Finally, eye tracking would also allow us to inspect target word skipping, which potentially provides insight into the information that is extracted from parafoveal words.

As far as semantics goes, we are aware of only two studies that adopted a similar paradigm. Carroll and Slowiaczek (1986) focused on how the structure of the sentence would affect lexical processing. They found that priming is influenced by the syntactic structure of the sentence, so that it is observed only when the semantically related prime and target appear in the same clause (e.g., 'The guard saluted *the king* and *the queen* in the carriage, but they didn't notice'). One issue with this experiment, however, is the lack of control over target word predictability. As observed in, e.g., Otten and Van Berkum (2008), there is widespread prediction of the upcoming word during sentence reading, which makes it difficult to unambiguously attribute Carroll's and Slowiaczek's results to cross–word priming. Facilitation may actually come from the on-line prediction of the target, to which the prime surely contributes as part of the sentence, but which it doesn't determine per se. The interaction between lexical representations in the mental lexicon may not be the driving force behind these results.

A similar issue affects the study of Camblin et al. (2007). These authors did gather data on target word predictability, but mean cloze probability in their semantically congruent condition was very high (averaging .36). Thus, on–line prediction based on sentence context may have played a major role in this experiment too, making unclear the contribution of lexical dynamics.

Things are not entirely clear on the morphological side either. For example, Paterson et al. (2011) investigated how the prior exposure to morphologically related words may influence target word processing. Their prime–target pairs were either semantically transparent (e.g., *marshy-marsh*), had only an apparent morphological relationship (e.g., *secretary-secret*), or were morphologically unrelated but as orthographically similar as in the previous conditions (e.g., *extract-extra*). Priming effects were observed in the semantically transparent pairs, but were absent in the remaining two conditions. This study clearly shows that the observed morphological priming effect is not driven by the prime–target (morpho-)orthographic relationship (e.g., Rastle et al., 2004). However, as the authors themselves acknowledge, it is impossible to establish whether the observed effect is morphological in nature or is rather a more general semantic effect, of the sort we would find with words like 'cat' and 'dog'—without such a pure semantic condition, this question cannot be addressed.

In the current study, we build on this previous work and devise a design that unambiguously assesses semantic and morphological cross–word priming during sentence reading. The core idea is quite simple. Primes and targets are embedded into sentences and put close together in a coordinating phrase (e.g., 'Paul entered a room with *a table* and *a chair*, which didn't really look like a kitchen'). Their semantic (S) and morphological (M) relationship is then independently manipulated, e.g., 'a table and a chair' (S+M+) vs. 'a dog and a chair' (S-M+) vs. 'some tables and a chair' (S+M-) vs. 'some dogs and a chair' (S-M-). Priming is taken to occur if fixations on the target word ('chair') are shorter after semantically and/or morphologically congruent primes.

This paradigm, as illustrated above based on English, has two main problems though. First, as already pointed out by Paterson et al. (2011), morphological relationship brings about orthographic relationship (plural words share a final –s), which makes it difficult to disentangle these two effects, in particular for shorter words. Second, the presence of determiners in the critical bit of the sentence is not ideal, for at least two reasons. Although articles are typically skipped during reading (e.g., Angele and Rayner, 2013), they could potentially attract at least some fixations, which would be difficult to handle—should they count as fixations on the target word? Or perhaps they would determine quite some more skipping of the target word itself? Also, and probably more relevant, articles contain morphological information, which would be extracted by the readers (foveally or parafoveally), thus blurring the whole picture—would morphological priming come from the content words or the determiners, or some cross–talk between the two? How does this affect the pattern of results, if it does at all? How would then results be comparable to those emerging from the individual word literature?

Here is where Slovenian, the language that we used for this experiment, turns out to be handy. Slovenian does not use determiners, so that primes and targets would sit alone in the critical coordinating phrase (e.g., *'miza in stol'*, 'a table and a chair'). Also, Slovenian is inflectionally very reach—it has 6 different cases, 3 different genders, and 3 different grammatical numbers, with noun declension introducing distinct suffixes for different combinations of the three.

Nouns can thus be inflected in the same way (i.e., in number and case), but still have orthographically different suffixes (e.g,. *'avtomobil-i'*, 'cars', plural, nominative; and *'učiteljic-e'*, 'teachers', plural, nominative,). This peculiarity of the Slovenian language thus enables us to rule out any orthographic contribution to morphological priming.

So, to sum up, we investigate here morphological and semantic cross–word priming during sentence reading. We do this in a natural reading, eye tracking paradigm that, taking advantage of the features of Slovenian, allows us to test these effects with a very ecological paradigm, virtually free of the confounds that affect the data available to date. This, we hope, will start bridging the current gap between the precise and mechanistic theories that we have for single word identification, and how the information extracted from single words is then used to build a complete linguistic message.

3.2 Methods

Participants

44 native Slovenian speakers (F=28) took part in the study. Their mean age and education was 34.2 (range=20–60) and 15.5 years (range=12–18), respectively. They all grew up in a monolingual environment and had normal or corrected-to-normal vision. Participants received an 8, 15 or 20 Euro compensation, depending on the distance travelled in order to reach the place of testing (SISSA, Trieste, Italy, or the University of Ljubljana, Slovenia). They all provided their informed consent to take part in the study before the beginning of the experiment.

Materials

The stimuli set comprised 40 sentences, in which two nouns appeared one after the other, separated by the conjunction *in*, and (e.g., *'kolesar ni bil pozoren na* ***avto*** *in* ***tovornjak*** *in je zato povzročil nesrečo'*; 'the cyclist was not paying attention to **a car** and **a truck** and therefore caused an accident'). In our design, the first noun (*avto*, car, in the example) is the prime word, while the second noun (*tovornjak*, truck, in the example) is the target word.

These sentences appeared in 4 different conditions, where primes and targets were (i) related in meaning, and inflected in the same grammatical number (*avto–tovornjak*, (a) car–(a) truck); (ii) related in meaning, but not inflected in the same grammatical number (*avte–tovornjak*, (some) cars–(a) truck); (iii) unrelated in meaning, and inflected in the same grammatical number (*lužo–tovornjak*, (a) puddle–(a) truck); (iv) unrelated in meaning, and not inflected in the same grammatical number (*luže–tovornjak*, (some) puddles–(a) truck). Both the carrier sentences and the target words were kept identical across conditions; only the prime varied, to determine morphological and/or semantic relatedness in a crossed, 2-by–2 design.

While constructing the sentences, we took a series of measures to guarantee a fair assessment of cross–word priming. First, the prime and the target word always appeared within the same syntactic clause (Carroll and Slowiaczek, 1986; Morris and Folk, 1998). Second, as anticipated above, primes and targets never shared the same orthographic suffix, and only shared the same final letter in 9 cases (5.6% of the stimuli set), so as to rule out any substantial contribution from form priming. As mentioned above, this is easily obtained in Slovenian through the use of prime and target nouns with different gender (e.g., *brisač-i*, towels, and *ležalnik-a*, deckchairs, are both dual nouns in the nominative case). Furthermore, target words never appeared in either clause or sentence final position, and were never followed by a comma—these conditions may in fact elicit wrap-up effects, with longer fixations depending on syntactic and/or semantic integration (Warren et al., 2009). Finally, we also controlled the position of the prime and the target word on the screen—they never appeared as the first or the last words in a line.

Primes and target features are illustrated in Table 3.1. They were matched as closely as possible for length and frequency. This latter was taken from the Slovenian corpus *Gigafida*. Sentences were 12 to 20 words long (mean=15.6), and included 63 to 138 characters overall (mean=92.3). The prime words came 19 to 62 characters into the sentence (mean=36.7). 25 sentences were displayed in two lines of text, whereas 15 occupied three lines of text on the screen.

In order to unambiguously asses the cross-word priming effects and also to prevent an excessive skipping of the target words, we made sure that these latter were not too predictable. A cloze probability task was set up (Kutas and Hillyard, 1984) with all the sentences that were then used in the experiment proper. A separate sample of 80 participants (F=54;

Table 3.1: Frequency and length of our stimuli across conditions. We report means and SDs. Frequency is taken from the Slovenian corpus *Gigafida*, log transformed, and based on word form.

	S+M+ prime	**S+M- prime**	**S-M+ prime**	**S-M- prime**	**Target**
Frequency	1.46 (0.54)	1.35 (0.53)	1.34 (0.58)	1.36 (0.52)	1.32 (0.50)
Length	6.60 (2.10)	6.57 (2.09)	6.97 (2.11)	7.25 (2.32)	6.57 (2.04)

S+/-: semantically congruent/incongruent; M+/-: morphologically congruent/incongruent.

mean age=32.38; age range=20–65), none of whom took part in the eye tracking experiment, were presented with the experimental sentences up to the pre–target word and were asked to complete them with the first word that came to mind. Because of our design, each target was anticipated by four different primes, in four otherwise identical sentences (e.g., *Kolesar ni bil pozoren na* ***avto/avte/lužo/luže*** *in* ***tovornjak*** ...). To make sure that target predictability was similar (and low) across conditions, all of these four sentences were tested in the Cloze Probability task, using a Latin Square design (each participant was presented with only one item in each sentence quadruplet, rotated across conditions). In the final stimuli set, no target word has a cloze probability higher than .2, with means and SDs across conditions as illustrated in Table 3.2.

Table 3.2: Mean (SD) cloze probability across conditions.

	S+M+	**S+M-**	**S-M+**	**S-M-**
Cloze probability	.05 (.05)	.06 (.07)	.01 (.03)	.01 (.03)

S+/-: semantically congruent/incongruent; M+/-: morphologically congruent/incongruent.

We also tested the strength of the semantic relatedness between the target words and their primes. A further separate sample of 21 participants (F=12; mean age=38; age range=25–58), none of whom took part in the eye tracking experiment or the cloze probability task, was asked to rate each prime–target pair for similarity in meaning on a 1-to-5 scale (1, not similar at all; 5, very similar). Because, again, each target was associated with two different primes (primes were tested only in one morphological form here), participants were rotated over conditions (related vs. unrelated) in a Latin Square design. The results of this pre–test are illustrated in Figure 3.1, and show that semantically congruent primes were rated as substantially more related to their targets than semantically incongruent ones, consistently across targets (mean and SD are 3.38 and 0.54, respectively, for the congruent condition; and 1.74 and 0.42 for the incongruent condition).

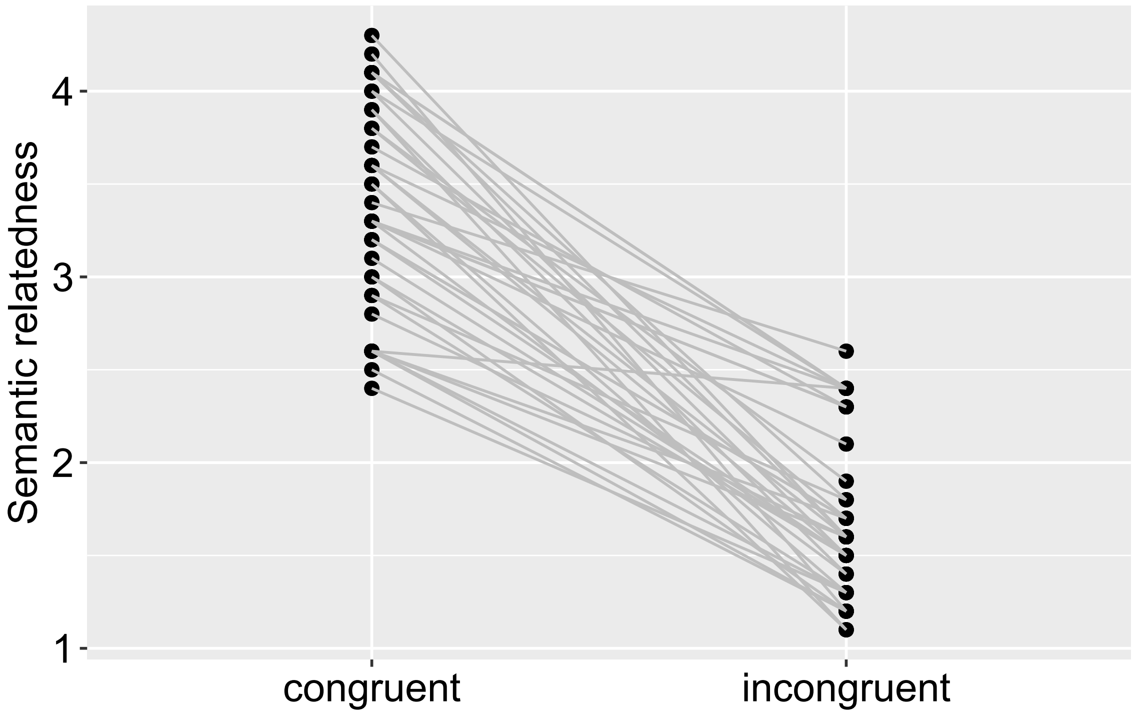

Fig. 3.1: Semantic relatedness in our Congruent (left) and Incongruent (right) pairs. Grey lines connect corresponding prime, those that were used with the same target.

Procedure

Participants were calibrated with a standard 9-point grid. Calibration was automatically checked with the fixation point before the beginning of each trial, and was repeated when necessary.

Participants were instructed to read silently the sentences at their own pace. On roughly 30% of the trials, sentence reading was followed by a 2AFC comprehension question, to ensure that participants were actually reading and understanding the sentences.

The trial timeline was as follows. A fixation point appeared on the screen for 250ms. Then the full sentence was displayed on the screen, and remained visible until the participants pressed the space bar, indicating that they have finished reading. This led to the presentation of either the fixation point of the following trial, or the comprehension question.

In order to reduce eventual repetition effects, each participant was presented with each sentence in only two out of the four experimental conditions, with a Latin Square design rotation. Each session was divided in two blocks, with the same two sentences never being part of the same block. To further minimize repetition effects, and also to reduce participants' awareness of the goal and the structure of the experiment, each block also included 60 filler sentences, which were not part of the experimental design and were not analyzed. The critical sentences were arranged across blocks in such a way that each block included 10 sentences per condition. Overall, each participant read a total of 200 sentences, in two separate blocks of 100 each. The experiment lasted about 50 minutes.

Apparatus

Participants sat 56 cm from the computer screen where the stimuli were displayed. Their head was stabilized through a chin rests. An `SR Eyelink 1000+` was used to record participants' eye movements, at a sampling rate of 1000 Hz. Eye movements were recorded from the dominant eye only.

Data analysis

Two interest areas were created for each sentence around the prime and the target words, using `SR Research Data Viewer` (SR Research Ltd., Kanata, ON, Canada). Trials with large gaze drifts were discarded.

Because we were interested in exploring the time course of the eventual cross–word priming, we analysed a number of target fixation metrics—first–of–many (FoM) fixation duration, first fixation duration, single fixation duration, gaze duration and total looking time. Moreover, in order to check for potential parafoveal priming, we also analysed target skipping and target–on–prime facilitation.

Data were analyzed with `R` (R Development Core Team, 2008), using `Rstudio` (RStudioTeam, 2016) and the `lme4` package (Bates et al., 2015) for fitting (generalised) linear mixed models. Model estimates and effect sizes were obtained using the package `Effects` (Fox and Hong, 2009). Continuous dependent variables were all log transformed in order to approximate a normal distribution and to achieve symmetrically distributed model residuals. They were modelled as a function of semantic and morphological congruency, with subjects and target words as random intercepts. Statistical significance was checked both for model parameters and for predictors overall. Effects were checked for their dependence on outliers following Baayen (2008)—models were re–run after excluding data points whose standardised residuals were larger than 2.5 in absolute value. There were no effects that would be significant only with (or without) outliers; reported here are the results of the models including all data points.

All data and analysis scripts are available to the reader here.

3.3 Results

All participants responded correctly to at least 95% of the comprehension questions (overall mean=98%, SD=1.64%), which suggests that they performed the task appropriately and understood the sentences very well. One participant was however excluded from the analysis because of her/his abnormally long fixations—her/his grand average gaze duration on the target words was 807.6ms, more than 300ms slower than the next slowest participant.

The overall descriptive statistics for the variables that we considered in the analyses are reported in Table 3.3.

Table 3.3: Means (and standard deviations) across conditions for the eye–tracking metrics that we considered in this study. Statistics are reported in ms or as proportions (for skipping rate), and are based on unaggregated data. Note: Skip, skipping rate; Prime, prime fixation duration (which tracks target–on–prime effects); FoM, first–of–many fixation duration; Single, single fixation duration; First, overall first fixation duration; Gaze, gaze duration; TLT, total looking time; S+/-, semantically congruent/incongruent; M+/-, morphologically congruent/incongruent.

	S+M+	S+M-	S-M+	S-M-
Skip	.066 (.249)	.067 (.251)	.048 (.214)	.041 (.199)
Prime	391 (350)	417 (367)	414 (356)	395 (339)
FoM	228 (110)	232 (135)	238 (149)	235 (133)
Single	243 (145)	237 (126)	256 (150)	249 (145)
First	237 (134)	235 (129)	249 (149)	243 (140)
Gaze	312 (189)	319 (196)	345 (194)	334 (196)
TLT	441 (312)	453 (304)	558 (379)	534 (368)

Starting from the earliest time point where priming could be reasonably expected, we checked whether target skipping might be influenced by the nature of the primes. Since the decision to skip the target word must be made prior to the target being fixated, this type of priming would be based on parafoveal information. Our dataset displays a relatively small number of target word skips (n=151), which amounts to ~ 5% of all trials. There is a significant effect of semantic congruency, $F(1, 2687) = 4.05$, $p = .04$ (the corresponding model parameter is also very close to significance, $z = 1.74$, $p = .08$). 95% confidence intervals (CI) for target skipping probablity are $[.025 - .059]$ and $[.015 - .039]$ for semantically congruent and incongruent primes, respectively. Pointwise model predictions reveal that targets are .014 more likely to be skipped if anticipated by a semantically related word. In contrast, our data suggest no effect of morphological congruency, $F(1, 2687) = .01$, $p = .92$, nor any interaction between semantic and morphological relatedness, $F(1, 2687) = .21$, $p = .64$. The model predictions for each design cell are illustrated in Figure 3.2.

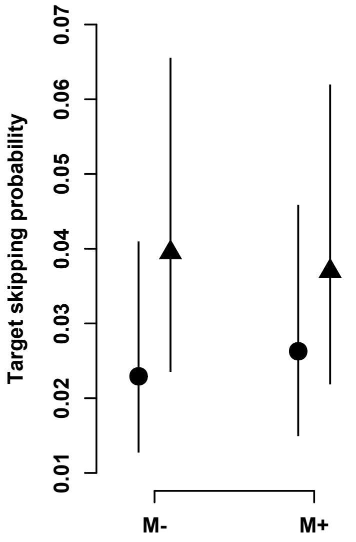

Fig. 3.2: LMM estimates for proportions of target word skip. Error bars represent 95% CIs. Note: ●/▲, semantically incongruent/congruent; M-/+, morphologically incongruent/congruent.

We also assessed priming based on parafoveal information in the form of a target–on–prime effect—essentially, we checked whether first–pass fixations on primes were shorter when the following target words were semantically and/or morphologically related[2]. This phenomenon would belong to the class of the hotly debated Parafoveal–on–Foveal (PoF) effects (e.g., Henderson and Ferreira, 1993; Inhoff et al., 2000; Just and Carpenter, 1983). Our data show no suggestion of any semantic, $F(1,2549) = .03$, $p = .85$, morphological, $F(1,2549) = .10$, $p = .75$, or interaction effect, $F(1,2549) = .10$, $p = .75$.

First-of-many (FoM) fixation durations do not reveal any effect of semantic congruity, $F(1,946) = .61$, $p = .43$, morphological congruity, $F(1,946) = .01$, $p = .92$, or interaction between the two, $F(1,946) = .06$, $p = .80$. The overall effect size is 5.9ms for semantic priming and .7ms for morphological priming. Figure 3.3a presents the model–based estimates for FoM. Interestingly, the lack of priming is not due to the skipping of the prime words—this only happened in 3.4% of the trials and, unsurprisingly, the model where these trials were excluded yields exactly the same results (all $p > .61$).

The same pattern emerges in single fixation duration, and in the duration of first fixations overall—no priming effect seems to emerge whatsoever in these metrics (all $p > .20$ and all effect sizes are below $<$ 6.9ms).

Gaze duration (GD), instead, reveals a solid semantic priming effect, $F(1,2535) = 5.12$, $p = .02$ (the corresponding model parameter is close to significance too, $t(2535) =< 1.17$, $p = .12$), with no morphological priming, $F(1,2535) = .39$, $p = .53$, nor interaction between semantic and morphological congruity, $F(1,2535) = .36$, $p = .54$. The estimated effect size is 18.6ms for semantic priming and 5.1ms for morphological priming. Figure 3.3b presents the model–based estimates for the four design cells. When only trials where the prime was fixated are taken into consideration, the semantic effect becomes even stronger, $F(1,2420) = 8.40$,

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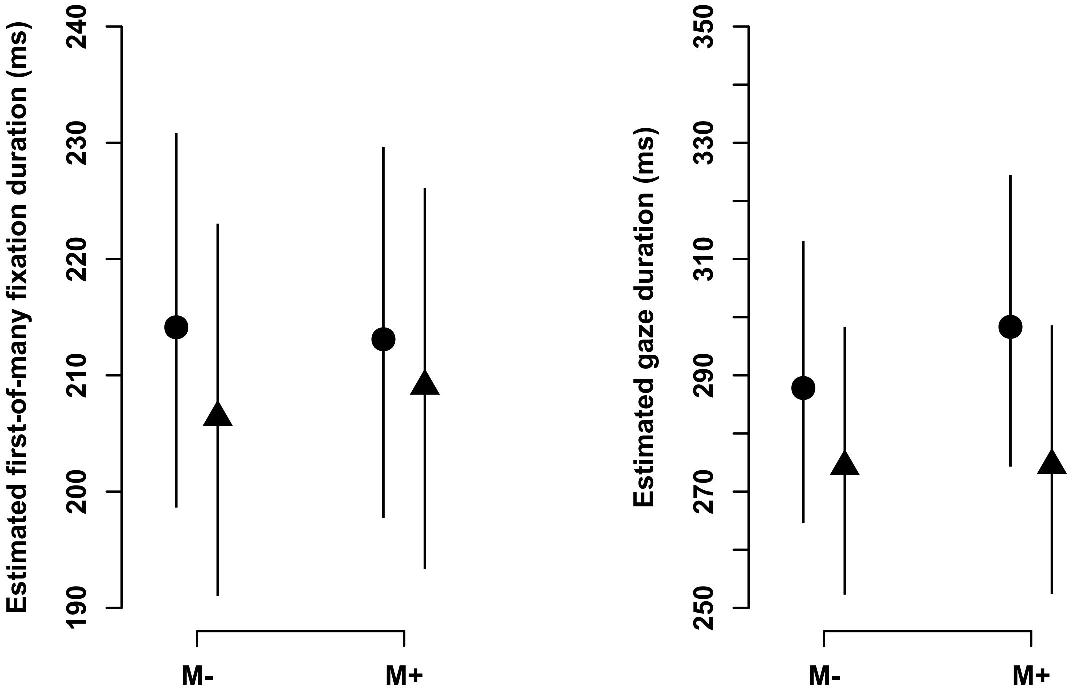
[2] Please note that, because the experiment was not designed specifically for testing this effect, priming is assessed across different targets here. Results should thus be taken with some caution.

p = .004 (model parameter, z = 1.54, p = .06). The morphological effect and the interaction between semantic and morphological relationships remains far from significance (all p > .47)

The same pattern emerges in the total viewing time—a solid semantic priming effect emerges, $F(1, 2535) = 17.63$, $p < .001$ (model parameter, $t(2535) = -2.50$, $p = .006$), with no morphological priming $F(1, 2535) = .26$, $p = .6$, nor interaction between semantic and morphological congruity $F(1, 2535) = .44$, $p = .5$.



(a) (b)

Fig. 3.3: LMM estimates for FoM fixation durations (panel a) and GD (panel b) on the target words. Error bars represent 95% CIs. Note: ●/▲, semantically incongruent/congruent; M-/+, morphologically incongruent/congruent.

3.4 Discussion

Building on similar previous paradigms and taking advantage of some handy features of the Slovenian language, we investigated semantic and morphological cross–word priming during natural sentence reading. Semantic facilitation emerged clearly, both in the skipping rate and in relatively late indexes of target fixation. This effect was not modulated by morphological agreement, nor we observed any morphological priming in the first place. Importantly, all these results emerged in a very ecological, natural sentence reading paradigm, thus revealing lexical dynamics as they likely emerge in our everyday reading experience. Moreover, these data extends our theoretical knowledge by showing us what happens when the visual word identification system is engaged with several words in a short amount time.

Our results confirm previous observations of cross–word semantic priming in natural sentence reading (Camblin et al., 2007; Carroll and Slowiaczek, 1986). Importantly, the current experiment allows to rule out word predictability in the sentence context as a source for this priming. Despite target words were barely predictable, and not differently so after related and unrelated primes, looking times were shorter on word N when word N-1 had a similar meaning. We can thus attribute the observed effect to the residual activation in the lexical system from word N-1 when a semantically related word N comes to the stage. This clearly indicates that there is no cross–word reset in the lexical system during sentence reading.

Whether this means that neighbouring words are taken up by the system simultaneously (Engbert et al., 2005; Snell et al., 2018b) or in rapid succession (Reichle et al., 2006), we cannot tell based on these data. The former hypothesis, however, would open a very interesting question—how does the lexical system keep track of information coming from different words? This is a nice challenge for computational models of reading and eye movements, which has only started to be taken up (see, for example, Snell et al., 2018b)

The time course of this semantic priming effect is also interesting. Facilitation emerged first in the skipping rate. This is perhaps not particularly surprising, given that the decision of whether to skip word N must obviously come while word N-1 is fixated; thus, the fact that information on word N-1 plays a role here is hardly unanticipated. But then, semantic priming did not emerge in earlier indexes of target fixation, such as FoM; and then 'came back' in later measures, such as GD. This contrast between FoM and GD would suggest a qualitative difference between the computations that determine overall first–pass looking time, which would be sensitive to word N-1 meaning; and those behind the earlier decision of whether to spend a second fixation on the foveal word, which would instead be independent of word N-1 semantics. Whatever precise interpretation one adopts for this time course, one thing is clear—it is not a matter of a mere activation decay for word N-1, or otherwise we would have observed stronger priming in earlier eye tracking indexes. Rather, these data suggest a dynamic, goal–specific cross–word processing in the lexical system during text reading, which is another interesting challenge for general theories of eye movements and visual word identification.

We were not able to observe any morphological priming instead. This better qualifies the evidence provided by previous experiments (e.g., Paterson et al., 2011)—when semantics and morphology are manipulated independently, the latter does not seem to give rise to cross–word processing savings during sentence reading. These data would suggest a re–interpretation of Paterson et al. (2011) results in terms of semantic similarity; 'marshy' would prime 'marsh' because these words have close meanings, not because they are morphological relatives. This would also explain the lack of any effect in opaque pairs like 'secretary' and 'secret' in the same experiment.

A note of caution is in order here, though. Especially in the individual word literature, morphological priming is typically addressed though shared stems or affixes, that is, in pairs like dealer–deal, or kindness–softness (e.g., Crepaldi et al., 2016; Marslen-Wilson, 2007; Rastle et al., 2004). Here, instead, primes and targets shared an abstract morphological inflection, which was denoted by different affixal, orthographic realizations (e.g., *avtomobil-a*, (two) cars, and *mačk-i*, (two) cats). This approach allows ruling out any orthographic (or phonological) contribution to morphological effects, which is why we adopted it. However, it may also justify the discrepancy between what we find here and the vast individual word priming literature showing solid morphological facilitation (e.g., Feldman, 2000; Gonnerman et al., 2007; Marslen-Wilson et al., 1994; Rastle et al., 2000).

Another very important insight brought about by cross–word priming is the stark contrast between semantic and morphological processing during sentence reading. Not only semantic facilitation emerges while morphological priming does not, but also we were unable to see any interaction between the two players—the semantic effect was not affected by whether primes and targets were inflected alike, nor the morphological effect was modulated by semantic similarity. This may suggest that abstract morphological agreement is processed, at least in part, outside of the (semantic) lexicon; and is reminiscent of theories supporting distinct lexical–semantic and morphological systems (e.g., Mcbride-Chang et al., 2008; Ramirez et al., 2014). Whatever theoretical interpretation one may want to adopt here however, these data are quite clear in showing a more locally encapsulated morphological system, which seems to prevent processing spillover between neighbouring words.

Finally, the cross–word semantic priming observed here in the skipping rate of the target word joins the club of recent papers showing semantic information uptake in the parafovea (e.g., Hohenstein and Kliegl, 2014; Schotter, 1996; Veldre and Andrews, 2016a,b). This adds to a long–lasting debate, which has been a major battlecamp between serial and parallel models of eye movements during reading (e.g., Reichle et al., 1998). The data presented here seem to favour the latter, as semantic processing of word N+1 would be difficult to justify in the former camp (but see Schotter et al., 2014, for an argument in this direction).

In addition to providing theoretical insight, the data described in the present paper open a few interesting questions, which the novel paradigm established here may help addressing. First, an important next step would be to study cross–word priming with different types of similarities between the prime and the target, such as case/gender agreement or orthographic similarity. This latter in particular may prove particularly interesting. Individual word priming suggests that orthographic overlap between the prime and the target may trigger lexical competition (e.g., Crepaldi et al., 2016; Davis and Lupker, 2006), which asks the question of whether we would see inhibitory cross–word priming between orthographically similar words.

Another interesting issue is related to the distance between primes and targets. In our sentences, they were only separated by a short, high-frequency conjunction word; and always sat within the same coordinating phrase. How much lag is cross–word priming able to overcome? And how would syntax play out here? We have observed that morphological inflection does not seem to affect semantic facilitation during sentence reading; would it be the same for perhaps more prominent morpho–syntactic factors such as phrase boundaries, or word movement traces?

4

Neural correlates of semantic and morphological priming in natural sentence reading

4.1 Introduction

The science of reading and visual word identification has progressed enormously in the last decades. However, our current understanding of reading seems to be divided between two fields of research (Snell et al., 2018b): while the first one focuses on individual word processing (e.g., Adelman et al., 2010; Forster and Veres, 1998; Marelli et al., 2015; Rastle et al., 2000; Xu and Taft, 2014), the second one focuses on eye movement control in text reading (e.g., Engbert et al., 2005; Reichle et al., 1998).[1] Despite the fact that both these fields importantly advanced our knowledge, not all aspects of the reading process can be addressed while they are kept in isolation. We addressed this issue in more detail in the previous chapter, where we emphasized the importance of starting to bridge this gap.

However, this gap becomes even greater when moving from behavioural and eye movement

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[1] There are of course some exceptions to this general trend, such as for example the recently released model of eye movement during reading *OB1-Reader* (Snell et al., 2018b), and recent studies with simultaneous recording of the EEG and eye tracking (e.g., Degno et al., 2018; Dimigen et al., 2011; Metzner et al., 2017).

research to the study of the neural mechanisms of reading. Despite the fact that the past years of technological advancement brought several tools that allow for the exploration of the neural mechanisms during natural reading (e.g., Amsel, 2011; Dimigen et al., 2011; Ehinger and Dimigen, 2018; Frömer et al., 2018; Smith and Kutas, 2015a,b), only a handful of natural reading studies up to date have taken advantage of these opportunities (Degno et al., 2018; Dimigen et al., 2011; Henderson et al., 2013; Kretzschmar et al., 2009, 2015; Metzner et al., 2017).

In these natural reading studies, the EEG signal and the eye movements are simultaneously recorded (coregistration, henceforth), while the participants are allowed to freely and spontaneously move their eyes as they process the presented text (Degno et al., 2018). With this, coregistration allows to time-lock the EEG signal to specific eye movements, such as a fixation on the target word of the presented text (Fixation-Related Potentials, FRPs). These act as natural EEG events and provide an exquisite opportunity to explore neural correlates under more natural reading conditions.

However, these studies are scarce at this point. Most of our current understanding of the neural signatures of semantic and morphological processing thus comes from Event-Related Potentials (ERPs) studies that are based on visual processing of individual words. Even when sentences are involved, the paradigm typically presents one word at the time (Rapid Serial Visual Presentation, RSVP), while the ERP components are locked to the onset of the target word on the screen.

Neural signatures of semantic processing are well-explored within this paradigm. Semantic processing is typically linked to the N400 ERP component, denoting a negative–going deflection starting around 250ms and peaking around 400ms after the stimulus onset, with a centro-posterior distribution (e.g., Federmeier, 2007; Hagoort, 2003; Kutas and Federmeier, 2000, 2011; Traxler and Gernsbacher, 2011). In semantic priming, N400 is larger (i.e., more negative–going), when the target word is preceded by semantically unrelated word, and smaller (i.e.,more positive–going) when the target word is anticipated by a semantically related word (e.g., Kutas and Hillyard, 1984; Rugg, 1985).

However, while the N400 component is well-explored, its exact interpretation is controversial. Traditionally, it has been interpreted either as an index of facilitated lexical access (e.g., Lau et al., 2009; Rugg, 1990), as an index of the access to the conceptual knowledge of a word (e.g., Federmeier, 2007; Kutas and Federmeier, 2000), or as an index of postlexical processes, such as the semantic context integration (e.g., Brown and Hagoort, 1993; Holcomb, 1993). However, regardless of the theoretical viewpoint one may adopt, it remains indisputable that the N400 provides information about the time course of the semantic processing, with its onset indicating the time point of the initial access to the word meaning (Dimigen et al., 2011).

Additionally, the N400 is also linked to morphological processing, despite the fact that the neural mechanisms behind morphological processing are still not fully understood (Leminen et al., 2018). The time course of morphologically complex word processing is namely assumed to be reflected in the N400 and a preceding N250 component, which is thought to reflect sublexical processing during visual word recognition (Holcomb and Grainger, 2006).

In priming paradigms, these components are generally larger when the target word is preceded by a morphologically unrelated prime, and generally smaller when it is anticipated by a morphologically related word (Holcomb and Grainger, 2006). This modulation has been consistently reported with stem (e.g., hunter–HUNT) and repetition priming (e.g., hunt–HUNT), both in masked (e.g., Holcomb and Grainger, 2006; Lavric et al., 2007; Morris et al., 2008) and overt priming paradigms (e.g., Lavric et al., 2010; Smolka et al., 2015). But the evidence is less consistent when it comes to inflectional morphological priming, which is most commonly addressed within the frame of regular and irregular inflection of English verbs. Here, some studies observed the N400 modulation with regular verbs, but not with the irregular ones (e.g., Rodriguez-Fornells et al., 2002), while others observed the N400 modulation both with regular and irregular verbs (in an auditory priming paradigm; Justus et al. (2011)). Additionally, other studies observed the biphasic N250/N400 modulation, but only with regular verbs (e.g., Rastle et al., 2015), while others observed it with both regular and irregular verbs (in masked priming paradigm; Morris and Stockall (2012).

Despite the fact that not all mechanisms are yet fully understood, the above ERP studies importantly advanced our current knowledge about the neural signatures of semantic and morphological priming, as well as our understanding of language processing in general. However, these well-established ERP paradigms importantly differ from the human natural reading experience in a number of ways (e.g., Degno et al., 2018; Dimigen et al., 2011; Metzner et al., 2017). Firstly, in RSVP paradigms, isolated words are typically presented in the middle of a screen, while the participants are instructed to fixate their gaze to the point where they will be presented, and to avoid blinking. Not only is this instruction unnatural, but it might also bring additional cognitive load, as the participants try to follow the given instruction and become aware of their otherwise unconscious eye movements. This could potentially have uncontrolled effects on the observed neural signatures. Further, each word is presented on a screen for a predetermined amount of time (typically around 400ms), which is significantly longer than the average time readers spend on a fixated word (with average fixation lasting 200-250ms; e.g., Sereno and Rayner (2003)). This notably slows down the reading speed, which could in turn have uncontrolled effects on the processing speed (Dimigen et al., 2011). Another important difference lies in how each individual word is visually processed to enter the reading system. In RSVP paradigms, the reader is forced to read each word, in a strictly serial order. This contrasts with normal reading, during which readers freely determine not only how long each word will be fixated, but also which word will be fixated next. We do not necessarily read in a strictly serial manner; some words are fixated more than once, while others are skipped, and regressive saccades towards previously fixated words are quite frequent (e.g., Dimigen et al., 2011). Finally, RSVP paradigms do not allow for the preprocessing of the upcoming words in parafoveal vision, which is of course possible (and quite used, actually) in normal reading (e.g., Degno et al., 2018; Dimigen et al., 2011).

All these differences make RSVP paradigms a vague approximation at best of the natural reading process, making it difficult, if not impossible, to establish to what extent RSVP findings would apply to normal reading (Dimigen et al., 2011). It is thus not surprising that the primary focus of the coregistration studies to date lies in the comparison between the results of the RSVP/ERP and more natural reading/FRP paradigms.

On the one hand, these comparisons indicate that, to a certain extent, FRP components are very similar to ERP components as obtained in RSVP paradigms. These similarities can be observed in their polarity and scalp distribution (Dimigen et al., 2011; Kretzschmar et al., 2009; Metzner et al., 2017), indicating that coregistration paradigms are feasible.

On the other hand, however, FRP components also importantly differ from ERP ones. One such difference is in their time course. Namely, the FRP components appear to have an earlier onset than typically observed in the RSVP paradigms (Dimigen et al., 2011; Kretzschmar et al., 2009; Metzner et al., 2017). The N400, for example, is traditionally marked as starting at around 200-250ms, and peaking at around 400ms (e.g., Federmeier, 2007; Hagoort, 2003; Kutas and Federmeier, 2000). This latency was indeed also observed in coregistration paradigms (e.g., Dimigen et al., 2011; Kretzschmar et al., 2009). But in parallel to it, a weaker N400-like effect topographies were observed already as early as around 120ms after the fixation onset (Dimigen et al., 2011; Metzner et al., 2017), indicating that the time line of word recognition in normal reading may differ from the one typically observed in RSVP

(Dimigen et al., 2011).

Another important difference comes from semantic and syntactic violation paradigms in natural reading. These kinds of violation paradigms are among the most well–established ERP paradigms, with semantic violations being associated with a modulation of the N400 amplitude (e.g., Federmeier, 2007; Hagoort, 2003; Kutas and Federmeier, 2000, 2011; Traxler and Gernsbacher, 2011), while syntactic violations are typically associated with a modulation of the P600 component (e.g., Carreiras, 2004; Friederici et al., 1993; Molinaro et al., 2011). In contrast, a recent coregistration study revealed that in natural reading semantic violations may also elicit a P600, while syntactic violations (when sentence final) also elicit an N400-like effect (Metzner et al., 2017). Additionally, the study also revealed that regressions play an important role in sentence processing, and are linked to P600. Namely, when the prediction violation was detected, it either triggered the biphasic N400/P600 effect accompanied by a regression, or the N400 effect, followed by sustained negativity (Metzner et al., 2017). With this, the study suggested that in natural reading the language processing system uses at least two different strategies to deal with confusing material—it can either fall back on the already processed part to recruit additional information (as reflected by P600 and regressions), or it tolerates the inconsistency (as reflected by N400 and sustained negativity in the absence of regressions; Metzner et al. (2017)).

All coregistration studies available to date thus suggest that natural reading paradigms indeed offer a more comprehensive picture of the neural signatures of reading, and speak up to the importance of shifting towards more natural experimental setups.

New FRP studies with more ecologically valid paradigms are thus already starting to emerge, but the number of these studies in natural reading is still scarce. It is thus not surprising that at this point there are, to our knowledge, no coregistration studies that would address either morphological or semantic priming in natural sentence reading, similarly to what we did in chapter 3.

However, when it comes to semantic priming in natural reading, there are a few previous FRP studies that can serve as a starting point. The first one among them did not introduce a sentence reading paradigm, but rather addressed FRP–based semantic priming in a word list reading task (Dimigen et al., 2012). To approximate the normal reading flow, prime-target pairs were embedded into a list of nouns, which the participants read at their own pace, from left to right. The results suggested an N400 modulation, with the unrelated, related and identical prime-target pairs eliciting largest, intermediate, and smallest N400 amplitudes, respectively (Dimigen et al., 2012). Additional evidence for an N400 modulation through semantic relatedness in natural reading was provided by another study. Despite the fact that they primarily addressed the issue of predictability, Kretzschmar et al. (2009) observed that the N400 component was the largest when an unpredictable word was also semantically unrelated to the most expected word. Whether these findings would extend to context-independent, cross-word semantic priming in natural sentence reading remains to be explored.

In the present experiment, we build on the novel paradigm, previously presented in the chapter 3. We explore whether, and to what extent, RSVP findings on semantic and morphological priming apply to natural sentence reading. We simultaneously record EEG and eye movements, in order to directly investigate the relationship between these latter and the neural signatures typically associated with word identification and, more generally, written language processing.

With this, we would like to contribute to a fairly new literature based on the simultaneous recording of EEG and eye movements during natural sentence reading. As such, the current project can only lean back on a very few previous coregistration studies available to date, and is thus quite exploratory in nature. We present here some preliminary results, which we take to constitute a pilot study, aiming to establish the feasibility of our experimental setup, data preprocessing, and data analysis.

4.2 Methods

Participants

14 right handed, native Slovenian speakers (F=8) took part in the study. Their mean age and education was 30.2 (range=22–42) and 16.2 years (range=12–20), respectively. They all grew up in a monolingual environment and had normal or corrected-to-normal vision. They all provided their informed consent to take part in the study before the beginning of the experiment, and received a 25 Euro compensation.

Materials

The stimuli set for this study was identical to the one used in the eye tracking study, presented in chapter 3.

Procedure

The task, instructions, eye tracker calibration procedure, and the experiment structure were identical to chapter 3 (see p. 56). The only difference was in the participants' control of the trial onset and offset via their fixations rather than button presses.

Sentence presentation was triggered by participants' fixation of the fixation cross. A complete sentence was than displayed, and remained visible until the participants fixated another cross, located at the bottom centre of the screen. This led to the presentation of either the drift correction fixation point of the following trial, or the comprehension question.

Apparatus

For eye tracking, the apparatus was identical to chapter 3 (see p. 56).

The EEG signal was recorded with a standard 64-channel (`BioSemi ActiveTwo`) system, at a sampling rate of 500 Hz. Additionally, 4 EOG channels were used to record the eye movement related EEG signal.

Coregistration of eye movements and EEG signal

Following the procedure described in (Degno et al., 2018), the stimulus display computer sent a message to the computer recording the eye movements, and a trigger to the computer recording the EEG signal, to mark the beginning and end of the experiment and of each trial. These triggers were used to establish an offline synchronization of the two recordings, which was done in `MATLAB`, with the `EYE-EEG` extension (Dimigen et al., 2011) of the `EEGLAB` toolbox (Dare and Shillcock, 2013).

Eye movement data preprocessing and analysis

Eye movement data were preprocessed and analyzed as in chapter 3 (see section *Data Analysis*, p. 74).

EEG data preprocessing

The EEG data preprocessing was performed in `MATLAB`, mainly through the toolbox `EEGLAB` (Delorme and Makeig, 2004). Initially, the data were band-pass filtered with a high-pass filter of .1 Hz and a low-pass filter of 30 Hz. Eye movement data were imported and synchronized, using the EEGLAB extension `EYE-EEG` (Dimigen et al., 2011). Continuous data was then segmented. The segments were time-locked to fixation onsets and included 0.1s before and

0.5s after fixation onset. Noisy channels were rejected, using the `EEGLAB`'s `pop rejchan` function (Delorme and Makeig, 2004) which combines three different methods: (1) Kurtosis treshold (set to 4σ); (2) joint probability treshold (set to 4σ); and (3) abnormal spectra (checked between 1 and 30 Hz, with a threshold of 3σ). Trials with extreme values ($\pm 300 \mu V$) were rejected before the eye tracker-supported Independent Component Analysis (ICA) was performed in order to identify the ocular artifacts. The independent components associated with ocular artifacts were identified and rejected using the `EYE-EEG` extension (Dimigen et al., 2011). `EYE-EEG` picks independent components that shared temporal covariance higher than .7 with eye movements, and mark them as oculomotor artifacts (Plöchl et al., 2012). Further, trials containing extreme values ($\pm 200\ \mu V$) and probability (4σ) were rejected. Data were then re-referenced to the average of all the scalp electrodes. The missing channels were interpolated before the data were divided into conditions, and baseline corrected to the 200ms before the fixation onset. Finally, the trials of all participants were concatenated for each condition.

EEG data analysis

EEG data statistical testing was performed through the nonparametric clustering method (Bullmore et al., 1999), as implemented in the `Fieldtrip lite` (Oostenveld et al., 2011) `EEGLAB` (Delorme and Makeig, 2004) toolbox for EEG/MEG analysis. This method offers a straightforward solution to the Multiple Comparisons problem. It builds on the fact that since EEG data has a spatio-temporal structure, real effects should occur over multiple temporally and spatially adjacent electrodes and time points (Groppe et al., 2011). As such, it offers two important advantages over parametric methods. It profits from the spatio-temporal structure of the EEG signal to effectively reduce the number of comparisons performed, and it does not require to make strong assumptions about the distribution of the data (Maris and Oostenveld, 2007).

Included were all scalp electrodes and all time points for a time window of 500ms, starting at the fixation onset. Further, data permutation with 5000 iterations was performed. On each iteration, the conditions were statistically compared via nonparametric permutation t test for each channel-time pair. The temporally and spatially adjacent t values that had p values $< .05$ were clustered together, forming candidate clusters. Then, a cluster-level statistic were calculated by summing the t values within each cluster. The significance of the candidate clusters was assessed via nonparametric permutation test, in which the conditions were randomly shuffled and cluster-level t values were calculated in the same manner as before. This step was repeated 5000 times, and on each iteration, the most extreme cluster-level t value was used to create a null distribution. The significance of the observed candidate clusters was than calculated as the proportion of expected t values under the null hypothesis that were more extreme than the observed ones.

4.3 Results

Behavioural results

All participants responded correctly to at least 89% of the comprehension questions (overall mean=96%, SD=1.99%), which suggests that they understood the sentences well and performed the task appropriately.

Eye movement results

Despite the small sample of participants included in this pilot study, we observe very similar results to those reported in chapter 3.

At this point there is no suggestion of any statistically significant effect in either skipping rates or GD (all $p > .2$). The observed pattern, though, resembles remarkably the data that emerged in the eye tracking–only experiment—target words are skipped more often and GD are shorter when they are anticipated by a semantically related word. The descriptive statistics for these variables are reported in table 4.1.

TVT was the most strongly significant measure in eye tracking only study, and also reveals results that are very similar to the previously observed ones. Here, a solid semantic priming effect emerges already with this small sample size, $F(1, 1136) = 12.22$, $p < .001$ (model parameter, $t(1136) = -2.07$, $p = .02$). No effect of morphological priming, $F(1, 1136) = 1.15$, $p = .28$, nor interaction between semantic and morphological congruity, $F(1, 1136) = .32$, $p = .57$, are observed, instead. Table 4.1 presents the descriptive statistics for this variable.

Table 4.1: Means (and standard deviations) across conditions for the eye–tracking metrics that we considered in this study. Statistics are reported in ms or as proportions (for skipping rate), and are based on unaggregated data. Note: Skip, skipping rate; Gaze, gaze duration; TLT, total looking time; S+/-, semantically congruent/incongruent; M+/-, morphologically congruent/incongruent.

	S+M+	S+M-	S-M+	S-M-
Skip	.064 (.245)	.073 (.260)	.036 (.188)	.064 (.245)
Gaze	291 (145)	311 (157)	316 (158)	325 (195)
TLT	362 (262)	370 (199)	464 (344)	459 (356)

EEG results

First, we compared semantically related (S+) to semantically unrelated (S-) conditions, collapsed across morphological congruency (M+M-). Unrelated primes generated a parietal negative deflection starting around 90ms, and reaching a maximum at around 150ms after the onset of fixation on the target word (Figure 4.1a). The observed difference does not reach significance at this point ($g = -1.45$, $95\% CI = [-2.52, -.37]$, $p = .18$). However, the effect size and the 95% confidence intervals do suggest that this component could denote a real effect once more participants will be tested. The same indication comes from the single subject analysis, which shows that the effect is going in the same direction for most of the subjects (Figure 4.1a, bottom left).

The comparison between semantically related and unrelated conditions also reveals another negative deflection, starting at a later time point, around 250ms, and reaching a maximum at around 400ms after the fixation onset (Figure 4.1b). The observed difference does not reach statistical significance either at this point ($g = -1.04$, $95\% CI = [-1.78, -.28]$, $p = .24$); but again, the effect size, the 95% confidence interval and the single subject analysis (Figure 4.1b, bottom left) also indicate that this effect may be solid enough to reach significance in the full sample.

Similarly, we compared morphologically related (M+) to morphologically unrelated (M-) conditions, collapsed across semantic congruency (S+S-). Unlike the semantic effects, morphological congruency does not indicate any difference between targets in the related and unrelated conditions (Figure 4.2). None of the classic morphological EEG signatures is close to significance (all $p > .40$). Based on the scalp distribution and time course of the effect that is the closest to significance ($g = -0.82$, $95\% CI = [-1.56, -.07]$, $p = .40$), we think that even this component is more likely noise rather than a real effect that would show up once appropriate statistical power is applied.

Further, we also analyzed the modulation of semantically related condition by morphological congruency. Compared to the S+M+ condition, S+M- targets elicit a parietal negative deflection, starting around 100ms, and reaching a maximum around 180ms after fixation onset (Figure 4.3). The observed difference does not reach significance at this point ($g = -1.33$, $95\% CI = [-2.32, -.35]$, $p = .18$), but again, the effect size, the 95% confidence interval and the single subject analysis (Figure 4.3, bottom left) would suggest that this component could denote a real effect once a full sample of participants will be tested.

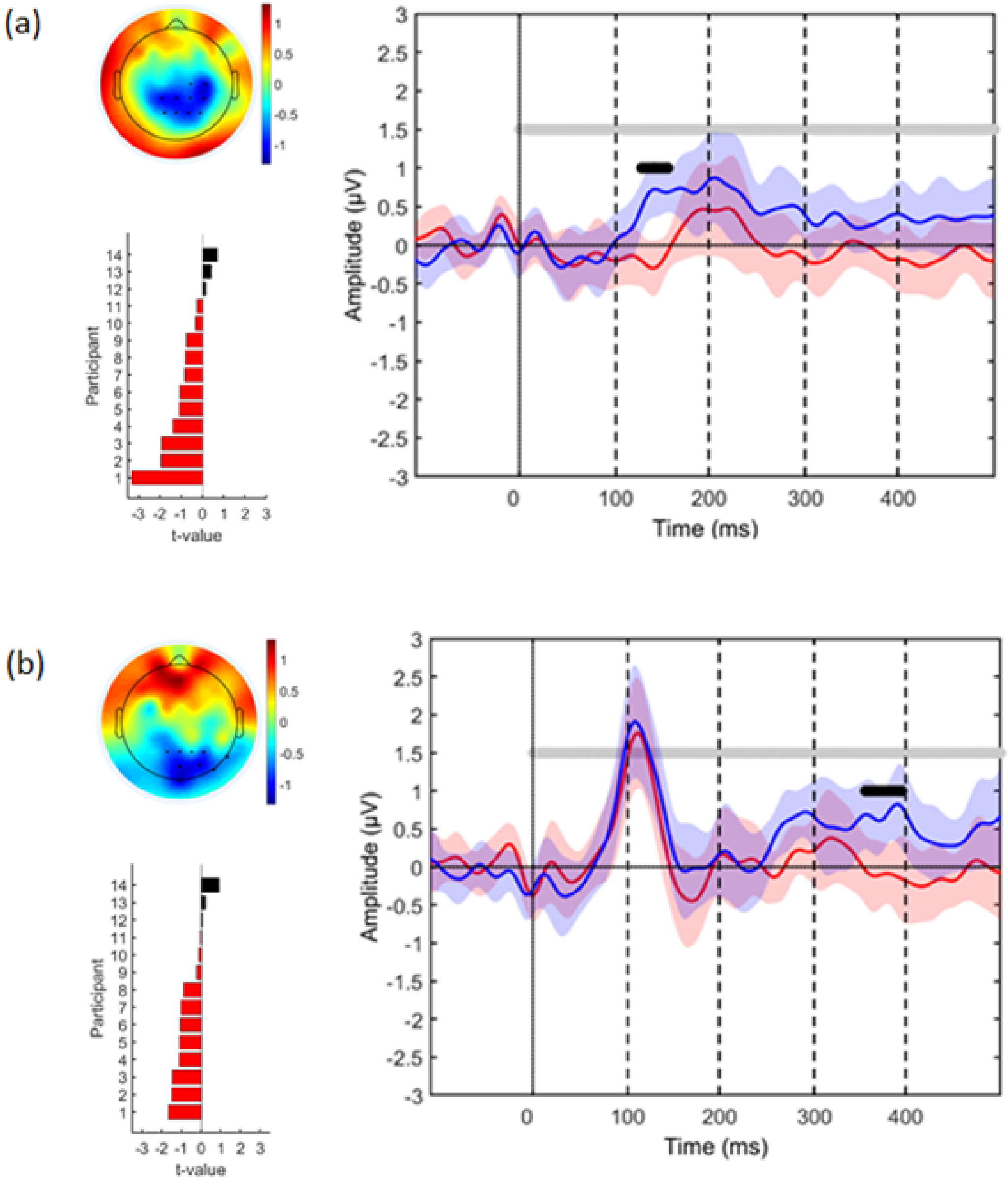

Fig. 4.1: Grand average FRPs for the first (a) and the second cluster (b) closest to significance. FRPs are time-locked to the fixation onset on the target word (solid vertical line), in response to the semantically related (blue) and unrelated (red) prime word. Error bars denote 1 SEM. The horizontal grey lines delimit the time window of interest, that is, the time points that were considered in the cluster analysis. The Horizontal black lines denote the time windows where at least one cluster got close to significance; the top left topoplot represents this cluster scalp distribution. The bottom left graph shows the strength of the statistical evidence for that cluster across participants.

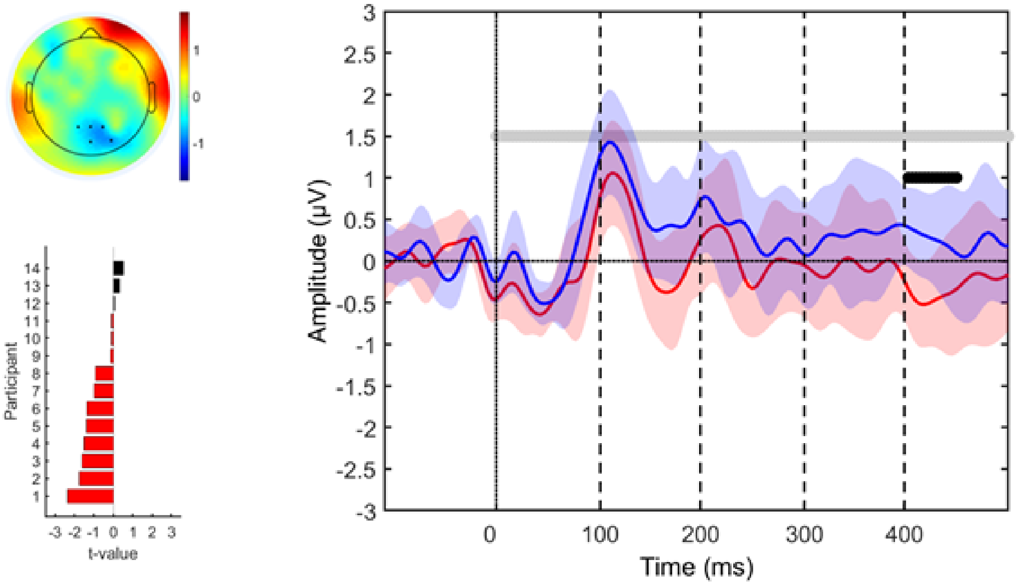

Fig. 4.2: Grand average FRPs, time-locked to the fixation onset on the target word (solid vertical line), in response to the morphologically related (blue) and unrelated (red) prime word. Error bars denote 1 SEM. The horizontal grey line delimits the time window of interest, that is, the time points that were considered in the cluster analysis. The Horizontal black line denotes the time windows where at least one cluster got close to significance; the top left topoplot represents this cluster scalp distribution. The bottom left graph shows the strength of the statistical evidence for that cluster across participants.

4.4 Discussion

Building on the paradigm established in our previous study (chapter 3), we presented here a natural sentence reading study, in which the subjects simply read for comprehension, while their eye movements and EEG data were simultaneously recorded. This enabled us to time-lock the EEG data to the fixation onset on the target words, which allowed us to gauge semantic and morphological cross-word priming in the scalp electrophysiology. We presented here the results of a pilot study, whose main aim was to establish the validity of our experimental design, data preprocessing and data analysis steps.

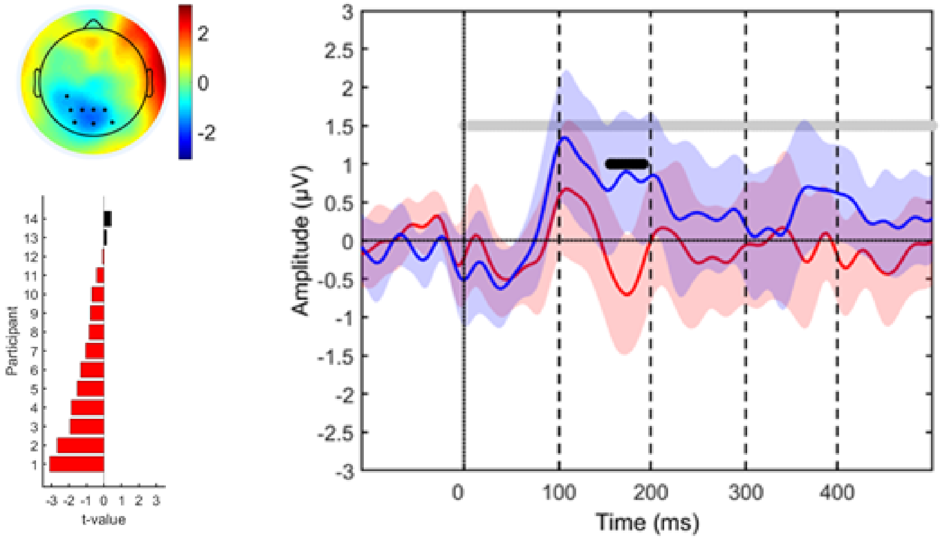

Fig. 4.3: Grand average FRPs, time-locked to the fixation onset on the target word (solid vertical line), in response to the semantically related/morphologically related (blue) and semantically related/morphologically unrelated (red) prime word. Error bars denote 1 SEM. The horizontal grey line delimits the time window of interest, that is, the time points that were considered in the cluster analysis. The Horizontal black line denotes the time windows where at least one cluster got close to significance; the top left topoplot represents this cluster scalp distribution. The bottom left graph shows the strength of the statistical evidence for that cluster across participants.

Due to the small sample size, no significant effect was observed at this point. This was hardly unanticipated. However, relying on estimated effect sizes, confidence intervals, cross–participants analyses, and the time–space characteristics of the clusters of electrodes that got closest to significance, we think we were able to identify a few results that may reflect solid effects, which would likely reach full statistical significance once an appropriately large sample of participants will be tested.

Semantically unrelated primes, compared to related words, seem to yield two negative deflections that reached the maximum at around 150ms and 390ms after the fixation onset.

Based on its polarity, scalp distribution and sensitivity to semantic priming, we believe that the first component may be related to what we would classically refer to as N400. If that is indeed the case, its time course is different from what is traditionally reported in RSVP paradigms (e.g., Federmeier, 2007; Hagoort, 2003; Kutas and Federmeier, 2000). This earlier onset, however, is not unexpected—similar time course shifts of the N400 effects in natural reading have also been reported in other coregistration studies (Dimigen et al., 2011; Kretzschmar et al., 2009; Metzner et al., 2017). Given that parafoveal preview is surely a benefit of natural reading, and is absent in RSVP paradigms, this earlier onset may not be that surprising—parafoveal processing may in fact kick off visual word identification quite before target fixation (Degno et al., 2018; Dimigen et al., 2011; Metzner et al., 2017). An additional reason for the earlier onset of the FRP components could be that saccades are self-initiated in natural reading. The time window in which the saccade is prepared and executed could also act as a processing foreperiod, during which readers optimize their temporal preparation, which in turn enhances their postsaccadic processing (Dimigen et al., 2011).

Interestingly, the second deflection does yield a latency within the range of the traditionally observed N400 effect. While its polarity and sensitivity to semantic priming would also suggest a connection between this later component and the classic N400, its scalp distribution seems to be more posterior.

Overall, these effects are similar to what was reported by (Dimigen et al., 2011) in a previous natural reading study that explored the predictability effect. In response to unpredictable words in the given context, the authors observed an earlier N400-like topography which emerged already between 120 and 160ms after the fixation onset, and was followed by a later negative-going component with an onset around 200-250ms and a peak at 384ms after the fixation onset. The authors connected both these components to the N400, with the first component indicating its early onset under natural reading conditions (Dimigen et al., 2011). Whether or not our observations could be interpreted similarly, it is difficult to say at this point in our research. Yet, we do think that the characteristics of the first component indicate that at least this FRP might reflect an early-onset N400-like effect. If that is the case, our results would provide additional evidence for the modulation of the N400 component through semantic priming, with the component being the largest when the target is anticipated by semantically unrelated word, as observed in the ERP/RSVP studies (e.g., Kutas and Hillyard, 1984; Rugg, 1985). Importantly, this modulation was observed under natural reading conditions and, as such, revealed the lexical dynamics and their time course as they likely emerge in our everyday reading experience.

In contrast, and similarly to what we observed in chapter 3, our data does not reveal any effect of morphological priming. This would suggest that sharing an abstract morphological inflection, at least when denoted by distinct orthographic (suffixal) realizations, does not modulate any of the components traditionally linked with morphological processing.

However, despite the lack of morphological priming, our results do suggest that morphological agreement modulates semantic priming. Namely, semantic effect seems to be affected by whether primes and targets are inflected alike. In fact, different inflections seem to elicit a negative-going component, which arises around 100ms and peaks around 180ms after the fixation onset. The time course and polarity of this effect are very similar to the characteristics of our first described component, observed with semantic priming. However, its scalp distribution does not reflect a similar topography, but rather a more posterior-right distribution. As such, this observed deflection cannot yet be clearly defined, but its characteristics may become clearer once the power of the study will increase.

This indication of potential morphological modulation of semantic priming is perhaps surprising, considering we did not observe such modulation in the eye tracking study (chapter 3). At this point, it is difficult to speculate about the reasons for this difference between the fixation durations and FRPs. Considering the fact that this discrepancy results from data from two separate experiments, one of which is under-powered, it is of course possible that the observed negative deflection will no longer be observed once the power of the study will be increased. The fact that at this point this FRP cannot be related any known ERP component in RSVP studies, may indicate towards this direction. If, however, this difference persist after the power of the study is increased, it could indicate that eye movements and FRP measures are not equally sensitive to morphological agreement. This could suggest that the two measures are not driven by shared underlying processes.

5

General discussion and conclusion

Indisputably, the last decades have witnessed an enormous progress in our understanding of the cognitive and neural mechanisms that support reading and visual word identification. We now know a great deal about how letters are identified to allow lexical access (e.g. Adelman et al., 2010; Davis et al., 2014; Grainger, 2008), how word representations interact in the human lexicon (e.g., Davis and Lupker, 2006; Forster and Veres, 1998), how meaning is extracted from these lexical dynamics (e.g Marelli et al., 2015; Meteyard et al., 2012), and how word morphology informs these processes (e.g Amenta and Crepaldi, 2012; Rastle et al., 2000; Xu and Taft, 2014).

Taking into account the fact that morphologically complex words represent a large proportion of words in most of the world's languages, and that they are the primary means for lexical productivity (Rastle, 2011), it is perhaps not surprising that the identification of morphologically complex words has attracted quite some attention in the psycholinguistic research. There is now broad consensus that complex words are processed through their constituent morphemes (Rastle, 2011). The most influential body of evidence in support of this tenet arguably comes from stem priming—when a target word is anticipated by a prime that share its stem, its processing is greatly facilitated, resulting in faster reaction times, reading times, and reduced N400 ERP component in lexical decision, eye tracking, and EEG paradigms, respectively.

Despite a rather substantial body of evidence on stem priming, not much is known about affix priming. An overview of the past literature has confirmed that other types of morphemes are rather underinvestigated. This is particularly true for inflectional morphemes, which were addressed by only a handful of studies, which also yielded conflicting evidence.

We tackled this underinvestigated topic in chapter 2, where we took advantage of the rich inflectional system of Slovenian to conduct two masked priming experiments. In the first one, we paired target words (e.g., *SESTRAM*) with nonword primes with either a shared stem (e.g., *sestrov*), a shared inflectional suffix (e.g., *kolesam*), or no morpheme at all. In the second one, we additionally introduced a condition where primes shared both a stem and a suffix (e.g., *sestram*). Our design allowed us to not only examine the existence of stem and/or suffix priming effect (Experiment 1), but, importantly, to directly compare the potential facilitation from the two different types of morphemes in the processing of an inflected word (Experiment 2). This comparison is particularly interesting, since stems and inflectional suffixes convey different kind of information.

The results of two masked priming lexical decision tasks suggested a solid effect of stem priming, while no effect of inflectional morpheme was found. Additionally, stem and suffix priming don't seem to interact; there is no additional advantage coming from sharing an affix when a prime and a target also share their stem.

Previous research suggests that (derivational) suffixes do play an active role in the processing of morphologically complex words (e.g. Crepaldi et al., 2016; Duñabeitia et al., 2008). Alongside the evidence in support of prefix priming (e.g., Anderson, 1992; Chateau et al., 2002; Reid and Marslen-Wilson, 2003), these findings were taken as sufficient evidence in support of the existence of a more general *affix priming effect*, indicating that all affixes play an active role in complex word identification. Here, we show that this might not be the case—inflectional suffixes, which carry morpho-syntactic information, do not seem to play such a role, at least in an inflectionally rich language like Slovene. Some evidence for the lack of inflectional priming was already available, but it was difficult to hold strong conclusions based on these data (Smolik, 2010; VanWagenen and Pertsova, 2014). Here, instead, we provide rather neat evidence, we believe, for this account.

While it is indisputable that experiments on isolated words importantly advanced our knowledge on word processing, it is also evident that they address language processing in a very limited linguistic context, and typically also under fairly unnatural task conditions (e.g., lexical decision task). As such, they substantially differ from the reading experience in which humans routinely engage in on an everyday basis. This issue was taken up in the second part of my thesis, where we investigated lexical identification in the context of sentence reading for comprehension.

More specifically, we tried to connect models of eye movement during sentence reading with models of the visual identification of isolated words. Recently, studies aiming to bridge this gap have started to emerge (Snell et al., 2018b); the experiments described in chapter 3 and chapter 4 follow very much in the same spirit. Our focus was on post-orthographic levels of lexical identification, so that we explored how lexical–semantic and morphological processing are affected by the engagement of the visual word identification system with multiple words in very rapid secession, as they occur under natural reading conditions. To this end, we investigated the phenomenon of *cross-word priming* during natural sentence reading. In the first study, participants simply read sentences for comprehension, while their eye movements were tracked. The sentences were presented on the screen in their full length, and remained visible until the participants indicated that they had completed their reading. Importantly, the critical sentences included two nouns, which appeared next to each other, separated by the conjunction *'and'*. The first noun was the prime word, while the second noun was the target word. Sentences appeared in four conditions, in which the target word remained constant, while the prime word was manipulated to be semantically and/or morphologically related to the target. Importantly, the experiment was conducted in Slovenian. This has brought two crucial advantages for our design: (i) Slovenian does not use determiners, which avoids any morphological cue on the upcoming noun. Primes and targets thus sat alone in the coordinating phrase (e.g., *miza in stol*, 'a table and a chair'). (ii) Slovenian is inflectionally rich. The nouns can thus be inflected in the same way (i.e., in number and in case), but have orthographically different suffixes (e.g., *avtomobil-i*, 'cars', plural, nominative; and *učiteljic-e*, 'teachers', plural, nominative. This allowed us to rule out any orthographic contribution to the morphological priming.

We found that words were skipped more when they were preceded in the sentence by semantically related primes. Also, cross-word semantic priming manifested itself in later (e.g., gaze duration), but not in earlier (e.g., first-of-many fixations) indexes of eye movement on the target words. We also found that semantic priming was not modulated by the morphological agreement between primes and targets; and that morphological agreement did not yield any priming per se. These results point to independent lexical-semantic and morphological processing during sentence reading, and suggest cross-word reset for the latter, but not for the former.

With this, our results confirmed previous observations of cross-word priming effect in natural sentence reading (Camblin et al., 2007; Carroll and Slowiaczek, 1986). However, unlike in previous work, our study design allowed us to rule out word predictability in the sentence context as a potential source of the observed priming. On the other hand, the lack of morphological priming effect in our experiment suggest a reinterpretation of the previously observed morphological cross-word priming in natural sentence reading, where the authors assigned the observed priming effect to the fact that the prime and the target (e.g., marshy-MARSH) were morphologically related (Paterson et al., 2011). In the light of our study, it could be argued that their observed effect emerged due to the semantic similarity between them, rather than due to their morphological relatedness.

However, a note of caution is in order here. In the isolated word literature, morphological priming is typically addressed through shared stems or affixes (e.g., kind–KINDNESS). Instead, in our experiment, primes and targets shared an abstract morphological inflection, denoted by different orthographic realization (e.g., *avt**a***, 'cars', dual, nominative–*MAČK**I***, 'cats', dual, nominative). While this conveniently allowed us to rule out any orthographic contribution to the morphological effect, it may also be the source of the discrepancy between our findings and the previous literature (mostly on individual word processing) suggesting the presence of the morphological facilitation (e.g. Gonnerman et al., 2007; Marslen-Wilson et al., 1994; Rastle et al., 2000).

From a slightly different perspective, making a transition from the study of words in isolation towards more natural reading paradigms is relevant also in investigating event-related brain potentials (ERPs; e.g., Kutas and Hillyard (1980); Rugg (1985). Here, sentence reading paradigms are not uncommon; but sentences are typically presented one word at a time, each word being presented for a fixed duration (i.e., Rapid Serial Visual Presentation, RSVP). While there's surely good reasons for this form of presentation (eye movements, an inevitable part of free reading, generate potentials that contaminate the EEG data), RSVP importantly differs from natural reading in several ways (chapter 4). Despite this fact, RSVP research assumes that reading processes and comprehension are not greatly affected by the highly constrained reading conditions (Metzner et al., 2017). But recent studies suggest that this might not be the case—while some studies demonstrate that the inability to regress towards earlier parts of the text compromises comprehension (e.g., Schotter et al., 2014), other coregistration studies indicate that word recognition in normal reading importantly differs from that typically observed in RSVP (chapter 4) (Degno et al., 2018; Dimigen et al., 2012, 2011; Kretzschmar et al., 2009; Metzner et al., 2017).

Chapter 4 in this thesis is an extension of the experiment described in chapter 3, where eye movements are tracked together with EEG in a Fixation Related Potentials (FRPs) study. We explored whether, and to what extent, RSVP findings on semantic and morphological priming would keep under more natural reading conditions.

We presented here the results of our pilot study, based on an initial sample of 14 individuals. The main aim was to establish the validity of our setup, data preprocessing and data analysis—overcoming the challenges of a simultaneous recording of eye movements and EEG under natural reading conditions has proven non–trivial.

Given the small sample on which we reported in this thesis, none of the observed effects reached significance at this point. Nevertheless, we observed potentially interesting FRPs in response to semantic priming—targets preceded by semantically unrelated primes elicited two negative going deflections, starting at around 90ms and 250ms, and reaching their peak at around 150ms and 400ms after the fixation onset, respectively. The early component's scalp distribution, polarity, and sensitivity to semantic priming do resemble what is classically reported as N400. Importantly, if the observed deflection would indeed turn out to be a solid effect once appropriate statistical power is applied, its time course would be very similar to the previously observed N400-like effect in natural reading coregistration studies (Dimigen et al., 2011; Kretzschmar et al., 2009)[1]. The onset of this N400-like effects is typically earlier than in RSVP paradigms, and so is in our data (chapter 4). Our study would thus provide additional evidence in support of the difference between the timeline of word recognition in normal reading and in RSVP paradigms (Dimigen et al., 2011).

On the other hand, we did not observe any effect of morphological priming at this point. However, it is worth noting that, contrary to what we observed in the eye tracking study, morphological relationship does further modulate semantic priming—semantically primed

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[1] Note however, that these studies examined the effect of predictability in sentence context, not lexically–based semantic priming.

targets showed a (weaker) negative going deflection in response to the morphologically unrelated prime-target pairs, with an onset around 100ms and the peak around 180ms after the fixation onset. Interestingly, this FRP cannot be traced back to any known ERP component in RSVP studies at this point.

The potential lack of morphological priming is not entirely surprising. Despite the fact that some of the previous ERP/RSVP studies did observe a morphological modulation of two components, N250 and N400 (Holcomb and Grainger, 2006; Lavric et al., 2007; Smolka et al., 2015), this effect is not consistently reported, particularly in connection to inflectional morphemes (e.g., Justus et al., 2011; Rastle et al., 2015; Rodriguez-Fornells et al., 2002). Additionally, as already mentioned above, primes and targets shared an abstract morphological inflection in our experiment, denoted by different orthographic realizations. To our knowledge, no previous RSVP or natural reading study addressed this type of morphological priming. However, the same lack of this kind of priming was observed in our previous, eye tracking study, suggesting a cross-word reset for morphological processing during sentence reading (chapter 3).

In summary, the work presented in this thesis builds on the characteristics of a heavily inflected language in order to better qualify the role of morphology in the visual recognition of complex words. As indicated above, this has been one of the most widely studied topics in psycholinguistics. The past four decades have brought to life numerous theories of visual word identification, which place different emphasis on the relative role of stems and affixes (Grainger and Beyersmann, 2017). Yet, the role of affixes is not yet fully understood. While some attention has been given to prefixes and derivational suffixes, the role of inflectional suffixes in complex word processing remains largely underinvestigated.

In the present thesis, we took to this issue in three different studies. Their overall results indicate that inflectional morphemes behave differently from stems and derivational morphemes in complex word recognition. This finding is particularly surprising in the light of previous research on affix priming. Namely, since it has been suggested that both prefixes and derivational suffixes play an active role in the visual identification of complex words (e.g. Chateau et al., 2002; Crepaldi et al., 2016; Dominguez et al., 2010; Duñabeitia et al., 2008), it could be assumed that these findings would be generalized to any kind of affix (Crepaldi et al., 2016). Yet, our results indicate that this might not be the case. A possible reason for this discrepancy between derivational and inflectional morphemes might lie in the nature of the information they carry. From this perspective, derivational morphemes, which typically carry lexical information, are more similar to stem morphemes than to inflectional morphemes, which only provide morpho-syntactic information.

Overall, our results suggest that inflectional morphological agreement is, at least partially, processed outside of the semantic lexicon; which is reminiscent of the theories supporting distinct lexical–semantic and morphologcal systems (e.g., Mcbride-Chang et al., 2008; Ramirez et al., 2014). Importantly, these results are not only observed in single word processing, but also in word processing during natural sentence reading. This indicates that the observed discrepancy between the role of morphemes with morpho-syntactic information and the ones with lexical information persists also when the visual word identification system deals with multiple words in a very rapid succession.

In conclusion, we believe that the present thesis provides an important contribution towards a more comprehensive understanding of reading and visual word identification. However, more research is of course needed before any strong claims can be made. For example, in our work, we focused only on inflectional morphemes. Thus, any comparison between different types of morphemes can only be made cross–linguistically at the moment. Further, in the single word research, we focused on the role of shared inflectional suffix, while in the sentence reading studies we focused on the role of shared abstract morphological inflection, denoted by different orthographic realization. How would the latter translate to single word processing? And how would the former behave within sentences? With this, our work also opens a few interesting questions, which the novel paradigms, established in this thesis, might help to address in the future research.

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