The dynamics of morphological processing in developing readers: A cross-linguistic masked priming study

Elisabeth Beyersmann, Petroula Mousikou, Sascha Schroeder, Ludivine Javourey-Drevet, Johannes Ziegler, Jonathan Grainger

To cite this version:

Elisabeth Beyersmann, Petroula Mousikou, Sascha Schroeder, Ludivine Javourey-Drevet, Johannes Ziegler, et al.. The dynamics of morphological processing in developing readers: A cross-linguistic masked priming study. Journal of Experimental Child Psychology, 2021, 208, pp.105140. 10.1016/j.jecp.2021.105140 . hal-03190528

HAL Id: hal-03190528

https://hal-amu.archives-ouvertes.fr/hal-03190528

Submitted on 6 Apr 2021

The dynamics of morphological processing in developing readers: A cross-linguistic masked priming study

Elisabeth Beyersmann[1], Petroula Mousikou[2,3], Sascha Schroeder[2,3], Ludivine Javourey-Drevet[4,6], Johannes C. Ziegler[4,5] & Jonathan Grainger[4,5]

[1]Macquarie University, Department of Cognitive Science and Macquarie Centre for Reading, Sydney, Australia

[2]Max Planck Institute for Human Development, Berlin, Germany

[3]University of Göttingen, Department of Educational Psychology, Göttingen, Germany

[4]Aix-Marseille Université, Centre National de la Recherche Scientifique, Laboratoire de Psychologie Cognitive, Marseille, France

[5]Aix-Marseille Université, Institute for Language, Communication, and the Brain, Marseille, France

[6]Aix-Marseille Université, Laboratoire Apprentissage, Didactique, Évaluation, Formation Marseille, France

Author Note

Correspondence concerning this article should be addressed to Elisabeth Beyersmann, Department of Cognitive Science, Australian Hearing Hub, 16 University Avenue, Macquarie University NSW 2109, Tel: +61 406 249 916, Email: lisi.beyersmann@mq.edu.au

Abstract

Empirical evidence from masked priming research shows that skilled readers can rapidly identify morphological structure in written language. However, comparatively little is known about how and when this skill is acquired in children. The present work investigates the developmental trajectory of morphological processing in a two-year longitudinal study that involves two large cohorts of German and French primary school children. The masked priming paradigm was used within an experimental design that allowed us to dissociate effects of (i) non-morphological embedded word activation, (ii) morpho-orthographic decomposition, and (iii) morpho-semantics. Four priming conditions were used: affixed word (*farmer-FARM*), affixed nonword (*farmity-FARM*), non-affixed nonword (*farmald-FARM*), and unrelated control (*workald-FARM*). The results revealed robust embedded word priming effects across both languages. However, morpho-orthographic and morpho-semantic effects were only evident in the French sample. These findings are discussed in the context of a theoretical framework that specifies the distinct roles played by embedded words and affixes, their distinct developmental trajectories, and how the intrinsic linguistic properties of a given language may impact on morphological processing.

Keywords: morphology; cross-linguistic; reading development; embedded words

Research on morphological processing in reading has shown that skilled readers can rapidly decompose letter strings into morphological units (e.g., Taft, 2003; Taft & Forster, 1975). However, comparatively little research has examined how and when children acquire this important skill (Rastle, 2018). Here, we report data from a two-year longitudinal study involving two large cohorts of German and French primary school children. The aim of the present study was to explore the developmental trajectory of children's morphological processing skills in visual word recognition, and to provide a more fine-tuned theoretical perspective of the mechanisms involved in identifying morphological sub-structures during reading. A masked primed lexical decision design was used that allowed for the dissociation of prefix, suffix, and embedded word priming effects across the two different languages.

Over the past 20 years, the masked priming paradigm has emerged as the gold standard for research investigating morphological processing in skilled readers (e.g., Forster, 1987; Giraudo & Voga, 2016; Grainger, Colé, & Segui, 1991; Longtin & Meunier, 2005; Longtin, Segui, & Hallé, 2003; Rastle, Davis, & New, 2004). One of the key findings from this area of research is that target word recognition is significantly facilitated by the prior presentation of a semantically transparent complex prime (e.g., *farmer-farm*) and a semantically opaque pseudo-complex prime (e.g., *corner-corn*), but not by the prior presentation of a mono-morphemic control prime (e.g., *cashew-cash*), suggesting that skilled readers initially decompose complex and pseudo-complex words into morphemic sub-units. Morphological segmentation effects in skilled readers have been widely replicated across several languages (for reviews, see Amenta & Crepaldi, 2012; Rastle & Davis, 2008), and have also, in more recent years, found support from studies combining masked priming with the recording of event-related potentials (e.g., Morris, Frank, Grainger, & Holcomb, 2007; for a review see Beyersmann, Bolger, et al., 2019).

As opposed to the widely replicated and robust pattern of morphological priming effects in adults, studies investigating such effects in children are much rarer and the obtained results tend to be more ambiguous (e.g., Beyersmann, Castles, & Coltheart, 2012; Lázaro et al., 2018; Quémart, Casalis, & Colé, 2011; Schiff, Raveh, & Fighel, 2012). What generally seems to be the case is that the kind of automatic morphological segmentation effects that are typically seen in adults, emerge at a relatively late stage in children's reading development, at a time when children have already mastered most other basic reading skills (Beyersmann et al., 2012; Dawson, Rastle, & Ricketts, 2018; Schiff et al., 2012). Importantly, the time of acquisition seems to vary across languages. For instance, a study with English-speaking third and fifth graders (Beyersmann et al., 2012) found significant priming effects with semantically transparent complex words (e.g., *farmer-farm*), yet no priming with semantically opaque complex words (e.g., *corner-corn*) was observed. These results indicate that English-speaking primary school children are sensitive to the "morpho-semantic" but not the "morpho-orthographic" relationship between the prime and the target, suggesting that they have not yet reached a level of automatization of form-based morphological processing during reading. Similarly, a study with Hebrew-speaking children provided evidence for morpho-semantic but not morpho-orthographic priming in fourth graders, whereas both morpho-semantic and morpho-orthographic priming effects were found in a group of seventh graders, suggesting that morpho-orthographic decomposition mechanisms are not acquired until high school (Schiff et al., 2012). In line with the findings from English and Hebrew, masked priming results from Spanish fourth, fifth, and sixth graders also show that morphological suffix priming effects (e.g., *lechero* - *journalero*) are only evidenced in the most experienced developing readers, but not in fourth and fifth grade (Lázaro et al., 2018). In contrast, an earlier onset for morpho-orthographic priming in children's reading development has been reported by a study with French-speaking third, fifth, and seventh graders (Quémart et al., 2011). All three groups of children revealed significant morpho-orthographic and morpho-semantic priming effects, which were comparable to those reported for adults. Hence, the results from this study suggest that French-speaking children might acquire morpho-orthographic decomposition mechanisms earlier in reading development than English, Hebrew, and Spanish speaking children.

Besides masked priming, the role of morphological processing in children's reading acquisition has also been explored using a range of other tasks, including for example simple lexical decision and naming tasks. Although these kind of tasks are open to strategic processing and therefore less able to shed light on the automatic processing that is known to be crucial for morpho-orthographic decomposition, there are a range of visual lexical decision studies that provide evidence for sub-lexical morphological processing in primary school children, which we will briefly summarize here (e.g., Casalis, Quemart, & Duncan, 2015; Dawson et al., 2018; Lázaro, Acha, Rosa, García, & Sainz, 2016; Lázaro, García, & Burani, 2015; Lázaro et al., 2018; Quémart, Casalis, & Duncan, 2012). For instance, Lázaro et al. (2016) showed that Spanish children responded faster to words with frequent suffixes than infrequent suffixes as early as Grade 2, suggesting that Spanish-speaking children are sensitive to affix representations from an early age. However, we note that the above mentioned Spanish masked priming results indicate that morpho-orthographic processing is not automatized until sixth grade (Lázaro et al., 2018), hence suggesting that sensitivity to affixes is not a sufficient condition for morpho-orthographic decomposition. Moreover, Quémart et al. (2012) reported evidence for a morpheme interference effect in French third and fifth graders (i.e., children found it harder to reject morphologically complex nonwords than morphologically simple nonwords), whereas Casalis et al. (2015)

showed that this effect is more prominent in French than in English fourth graders. These findings further showcase the importance of cross-linguistic differences in the developmental trajectory of morphological form processes.

Questions thus still remain concerning the generalizability of morphological priming effects across different languages. Intrinsic linguistic properties, such as orthographic transparency and morphological productivity, influence the way morphemes are processed within specific languages (e.g., Beyersmann et al., 2020; Mousikou et al., 2020). German and French differ in two important aspects, morphological productivity and orthographic complexity, which leads to two key predictions, outlined below.

First, as shown by methods developed to quantify morphological productivity across different languages (e.g., Juola, 1998, 2008; Kettunen, 2014), German is morphologically more complex than French. Sadeniemi, Kettunen, Lindh-Knuutila, and Honkela (2008) argue that the productivity of German morphology is likely due to the abundant presence of compound words (e.g., Creutz & Lagus, 2005; Creutz, Lagus, Lindén, & Virpioja, 2005; Fleischer & Barz, 1995; Meyer, 1993). In line with these quantitative differences, it has been shown that German skilled readers are more sensitive than French skilled readers to the processing of embedded stems, presumably because of the highly productive German compounding system and the frequent exposure to stem + stem concatenations in the German language (Beyersmann et al., 2020). These intriguing findings from adults predict that the activation of embedded stems would play a particularly important role in German reading acquisition compared to reading acquisition in a language with a sparser compounding system like French. **In contrast, although compounding also exists, even if to a lesser extent, in French (Nicoladis & Krott, 2007), French compounds are often non-concatenated (e.g., *chef de police* [engl. chief of police]) or**

hyphenated (e.g., *grand-père* [engl. grandfather]). As a result, French developing readers are primarily exposed to stem + affix concatenations (i.e., prefixed and suffixed words). Morphological segmentation into stems and affixes therefore represents the key to morphological processing in the French language and predicts that French children may benefit from morphological structure sooner in their reading development compared to German children. The goal of the present study was to put these predictions to test by directly comparing the magnitude of embedded stem and morphological priming effects across two large cohorts of German and French speaking third and fourth graders[1].

Second, although German and French are both characterized by a rich system of inflectional and derivational affixes (e.g., Rey-Debove, 1984; Roelcke, 1997), the two languages differ with respect to their "orthographic complexity" (Schmalz, Marinus, Coltheart, & Castles, 2015), which is known to affect children's reading acquisition (e.g., for a comparison of 7 different orthographies, see Aro & Wimmer, 2003). French is orthographically more complex than German (De Simone, Beyersmann, Mulatti, Mirault, & Schmalz, under review; Schmalz, Beyersmann, Cavalli, & Marinus, 2016), due to its large number of complex letter-sound correspondences (e.g., Schmalz et al., 2016; Schmalz et al., 2015; van den Bosch, Content, Daelemans, & de Gelder, 1994). The different degrees of complexity of the French and German orthographies are also reflected in the number of grapheme-to-phoneme correspondence (GPC) rules implemented in the Dual Route Cascaded (DRC) models of German (Ziegler, Perry, & Coltheart, 2000) and French (Ziegler, Perry, & Coltheart, 2003). The number of rules,

---

[1] We note that cross-linguistic differences in complex word recognition as a function of morphological productivity (Beyersmann et al., 2020), do not necessarily generalize to the field of spoken word production (Mousikou et al., 2020). Mousikou et al. (2020) used a reading aloud task to study children's ability to map letters onto sounds, showing that children's reading aloud skills varied not as a function of morphological productivity, but as a function of orthographic consistency. This finding is not inconsistent with the findings of the present study, because the consistency with which letters in a certain language map onto phonemes might be critical for reading aloud, but not necessarily for visual word recognition.

particularly the number of complex rules, and the number of context-sensitive rules is higher in French than in German (see also Table 1 in Schmalz et al., 2015). French contains many multi-letter rules, where several letters are required to denote a single phoneme (e.g., *aient* → /ɛ/ in French), as well as many context-sensitive regularities, where surrounding letters affect a grapheme's pronunciation (e.g., in French, the letter *g* is pronounced as /ʒ/ when followed by an i or e, as in *gélatine*). Therefore, learning to read within a complex orthography may be more likely to shift children's reliance from single letter decoding onto multi-letter decoding early on in reading development (Mousikou et al., 2020). This thus makes a second important prediction that French readers should be more proficient at processing affixes compared to German readers, and would also explain why French children already show evidence for morpho-orthographic processing as early as Grade 3 (Quémart et al., 2011). Although these initial findings logically imply that the developmental trajectories of morphological processing skills should vary across languages like German and French, this hypothesis has never been put to test in a tightly controlled cross-linguistic examination.

The goal of the present masked priming study was to investigate the development of embedded word and morphological processing in German and French primary school children by building on the ”word and affix” model of complex word reading (Beyersmann & Grainger, in press; Grainger & Beyersmann, 2017), a theoretical framework that clearly dissociates the different contributions of embedded word activation and morphological segmentation in children's reading development. The model is not only amongst the most recent theoretical frameworks having emerged from decades of masked priming research in children and adults, but is also unique in the sense that it specifies the multiple stages of reading development that are required to reach the same level of morphological processing skills that are typically seen in adults. The latest version of the model (Beyersmann & Grainger, in press) implements three key mechanisms that are at play during the early stages of complex word recognition: edge-aligned embedded word activation, morpho-orthographic full decomposition, and feedback from semantics (see Figure 1). The model predicts that embedded words and whole words are activated via a whole-word pathway, by simply mapping letters onto whole-word representations in the orthographic lexicon, whereas morpho-orthographic full decomposition occurs via a separate pathway by which letter strings are decomposed into their component morphemes. Active units in the orthographic lexicon are then mapped onto a third layer of semantic representations. Based on bidirectional links between the orthographic lexicon and semantics, the model accounts for semantic influences on lexical processing via feedback connections from semantics.

One of the key predictions of this model, which is of particular relevance to the current investigation, is that beginning readers can draw on their whole-word knowledge when discovering form-meaning relationships between morphologically complex words and their embedded stems. Embedded stems represent a critical starting point in children's development of morphological processes (Beyersmann, Grainger, & Castles, 2019), based on which a specialized morphological parsing system can develop once children gain more reading experience (Beyersmann & Grainger, in press; Grainger & Beyersmann, 2017). Grainger and Beyersmann argue that the development of the morphological parsing system goes through three consecutive stages, by which children first acquire the ability to identify embedded words, then the ability to process morpho-semantics (by discovering form-meaning regularities), and finally the ability to decompose words into morpho-orthographic subunits (see also, Beyersmann et al., 2012). How quickly children move through these three developmental stages might differ between different languages, as is already shown in the above-mentioned studies with English-, Hebrew-, and French-speaking children (Beyersmann et al., 2012; Quémart et al., 2011; Schiff et al., 2012). Our goal was therefore to closely monitor the developmental stages of morphological processing in two large cohorts of German- and French-speaking third and fourth graders, using masked morphological priming.

The experimental design was chosen such that it allowed us to determine the unique contribution of non-morphological embedded word priming, morpho-orthographic priming and morpho-semantic priming. Four priming conditions were created for each target word. These included an affixed word prime (e.g., *farmer-FARM*), an affixed nonword prime (e.g., *farmity-FARM*), a non-affixed nonword prime (e.g., *farmald-FARM*), and an unrelated prime (e.g., *workald-FARM*). To examine the influence of embedded word processing, the non-affixed condition was compared against the unrelated control condition[2]. To investigate the influence of morpho-orthographic processing, the affixed nonword condition was compared against the non-affixed condition. Finally, to explore the influence of morpho-semantic processing, the affixed word condition was compared against the affixed nonword condition. We note that the latter comparison raises a complex issue of prime lexicality. Under masked priming conditions, orthographically related nonword primes tend to have a greater facilitatory impact than word primes, due to lexical competition between word prime and the word target (also referred to as the "prime-lexicality effect"; Forster & Veres, 1998). However, Grainger and Beyersmann

---

[2] We interpret the difference between these two conditions in terms of embedded word processing, and not in terms of lower-level orthographic processing. Embedded word priming effects are thought to be modulated by the morphological family size (Beyersmann & Grainger, 2018) and conditional suffix probability of the embedded word unit (Grainger & Beyersmann, 2020), suggesting that embedded words are activated to the level of the lexicon. Moreover, although words produce priming when embedded in edge-aligned string positions (e.g., *bookpime-BOOK*), this is not the case for words embedded in mid (e.g., *pibookme-BOOK*) or outer string position (e.g., *bopimeok-BOOK*), supporting the idea that orthographic prime-target overlap alone is not sufficient to produce priming (Beyersmann et al., 2018).

(2020) showed that the effect of prime lexicality extends to non-affixed primes including the target word as an embedded letter sequence (e.g., inhibitory priming from *dragon-DRAG* but not *dragip-DRAG*), but that in complex words, the effect of prime lexicality is counterbalanced by morpho-orthographic complexity (i.e., equal priming for *corner-CORN* and *cornry-CORN*). We therefore reasoned that any additional priming in the affixed word condition (*farmer-FARM*) could only be due to the shared morpho-semantic relationship between the prime and the target.

Cross-linguistically, we hypothesized that German speaking children should rely primarily on the activation of embedded words rather than on morpho-orthographic and morpho-semantic processing (Beyersmann et al., 2020), and that evidence for embedded word priming should emerge as early as Grade 3 (Hasenäcker, Beyersmann, & Schroeder, 2016, 2020). French speaking individuals were also expected to show evidence for significant embedded word priming (Beyersmann, Grainger, Casalis, & Ziegler, 2015), but additionally demonstrate greater reliance on morpho-orthographic and morpho-semantic processing mechanisms, compared to their German peers . Based on prior evidence, we predicted that morpho-orthographic segmentation effects in French would already emerge as early as Grade 3 (Quémart et al., 2011).

Finally, our research aimed at comparing the processing of prefixed and suffixed nonwords in French and German. Accordingly, four additional priming conditions were created using prefixed items (e.g., affixed word: *reload-LOAD*; affixed nonword: *exload-LOAD*; non-affixed nonword: *erload-LOAD*; unrelated control: *erwork-LOAD*). Based on the idea that both edges of the letter string act as anchor points for embedded word activation (Beyersmann & Grainger, in press; Fischer-Baum, Charny, & McCloskey, 2011; Grainger & Beyersmann, 2017), we hypothesized that comparable embedded word priming effects should be observed in both prefixed items (with final embedded words) and suffixed items (with initial embedded words), under the assumption of parallel letter processing. In addition, the study's aim was to test differences in morpho-orthographic and morpho-semantic priming effects between prefixed and suffixed items. Prior work from skilled readers has shown that suffixed words tend to be subject to early, morpho-orthographic segmentation, whereas prefixed words appear to have a quasi-lexical status, and are therefore more likely to be subject to post-lexical, morpho-semantic processing (e.g., Beyersmann, Ziegler, & Grainger, 2015; Kim, Wang, & Taft, 2015). Other studies, however, have failed to find processing differences between prefixed and suffixed words (Beyersmann, Cavalli, Casalis, & Colé, 2016; Heathcote, Nation, Castles, & Beyersmann, 2018; Mousikou & Schroeder, 2019). Whether or not prefixes and suffixes have a different status in the reading system therefore continues to be a matter of debate. Here, our aim was to examine differences between prefixes and suffixes within the context of reading development and to test, for the first time, if children are more efficient at segmenting items containing prefixes than items containing suffixes, or vice versa. Developing readers initially learn to decode the letters of a word serially, from left to right, which may promote the acquisition of a left-to-right scanning mechanisms in visual word recognition (e.g., Acha & Perea, 2008; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Korne, 2003). As a result, prefix processing may emerge earlier during reading development than suffix processing. However, it is also possible that children acquire the ability to extract suffixes sooner than prefixes, because suffixes are less likely to modify the meaning of the stem morpheme.

Method

Participants

A total of 304 children, 171 French and 133 German participated in the study. Children were assessed twice with a one-year interval: once in Grade 3 and once in Grade 4 (5-6 months into the school term in both grades). Three German children had to be excluded, because they were foreign language speakers who had spent less than two years living in Germany, and another three children were excluded because they had reported learning disabilities. Moreover, several children who participated in the first testing session were no longer available in the following year, at the time of the second testing session, and therefore were also removed from the sample. This reduced the total number of participants to 139 French and 113 German children (see Table 1). Participants were native speakers of their respective language, had normal or corrected-to-normal vision, and reported no hearing, reading, or language difficulties. Prior to participating in the study, the children's parents provided written, informed consent.

Materials

Two different item sets were selected for each language: a set of prefixed items and a set of suffixed items (see Appendix A for a full list of materials). The prefixed materials included 48 French target words and 48 German target words, which were matched as closely as possibly on number of letters, syntactic word class, and word frequency. Word frequency was extracted from Manulex (Lété, Sprenger-Charolles, & Colé, 2004) for French, and childLex (Schroeder, Würzner, Heister, Geyken, & Kliegl, 2015) for German.[3] All target words in the prefixed set corresponded to infinitive forms of verbs. The psycholinguistic properties of the French and German words are displayed in Table 2. Each target was preceded by an affixed word prime (*recharger-CHARGER* [recharge-CHARGE]; *mitdenken-DENKEN* [think along-THINK]), an affixed nonword prime (*excharger-CHARGER* [excharge-CHARGE]; *hindenken-DENKEN* [think towards-THINK]), a non-affixed nonword prime (*fecharger-CHARGER* [fecharge-CHARGE]; *kardenken-DENKEN* [karthink-THINK]), and an unrelated prime (*felaisser-*

---

[3] It is worth noting that the comparison of word frequencies in the two languages is not straightforward, because of the different sizes of the corresponding corpora.

CHARGER [feleave-CHARGE]; *karhasten-DENKEN* [carpaint-THINK]). The French prefixed words included the prefixes *dé-*, *en-*, *pré-*, and *re-*, and the German prefixed words included the prefixes *auf-*, *mit-*, *ab-*, and *an-*, which were each repeated 12 times. The French and German prefixed words were matched on number of letters.

Prefixed nonword primes were created using the target word as a stem (e.g., *charger*) and a prefix (e.g., *ex-*), which in combination with the stem resulted in a nonword (*excharger*). To ensure that the selected stem-affix combinations did not result in another existing word, while controlling for stimulus length and affix repetition, the prefixes in this condition were different from the prefixes in the affixed word condition. The French prefixed nonwords included the prefixes *in-*, *bi-*, *dis-*, and *ex-*, and the German prefixed nonwords included the prefixes *hin-*, *vor-*, *um-*, and *zu-*. The French prefixes were each repeated 12 times. In German, it was impossible to use all prefixes an equal number of times, because German prefixes are highly productive and often result in real words when combined with a stem. Therefore, the German prefixes *hin-* and *um-* were repeated 16 times, and the prefixes *vor-* and *zu-* were repeated 8 times. Non-suffixed nonword primes were created using the target word as a stem (e.g., *charger*) and a non-morphemic letter-sequence (e.g., *fe-*), which in combination with the stem resulted in a nonword (*fecharger*). Unrelated primes were non-affixed nonwords that were orthographically unrelated to the target. All nonwords contained orthographically legal letter combinations and were pronounceable. Within each language, the items in the four prime conditions were matched on length.

The suffixed materials included 48 French target words and 48 German target words, which were matched as closely as possible on number of letters, syntactic word class, and word frequency. As opposed to the prefixed item set which consisted of a selection of verb targets, all target words in the suffixed set were either nouns or adjectives. This choice of materials was constrained by the German language: Due to the high productivity of most German prefixes, which result in real words when combined with a stem, it was practically impossible to use the same affixes in the affixed word and affixed nonword conditions. To ensure that the items in the two languages were comparable, we opted for creating the German and the French items using the same procedure. Each target was preceded by an affixed word prime (*fillette-FILLE* [little girl - GIRL]; *steinchen-STEIN* [little stone - STONE]), an affixed nonword prime (*fillible-FILLE* [girlable-GIRL]; *steinkeit-STEIN* [stonity-STONE]), a non-affixed nonword prime (*fillache-FILLE* [girlach-GIRL]; *steinucht-STEIN* [stonel-STONE]), and an unrelated prime (*gommache-FILLE* [gummach-GIRL]; *piratucht-STEIN* [pirate-STONE]). The French suffixed words included the suffixes *-esse, -ette, -eur,* and *-ier*, and the German suffixes words included the suffixes *chen, -haft, -heit,* and *-lich,* which were each repeated 12 times.

Suffixed nonword primes were created using the target word as a stem (e.g., *fille*) and a suffix (e.g., -*ible*), which in combination with the stem resulted in a nonword (*fillible*). Again, to maintain nonword status in this condition, the suffixes used to create suffixed nonwords were different from the suffixes used in the suffixed word condition (see Appendix A). The French suffixed nonwords included the suffixes *-able, -ible, -oir*, and *-ure*, and the German suffixed nonwords included the suffixes *-keit, -isch, -ling*, and *-lein*. The French suffixes were each repeated 12 times. The German suffixes *-keit* and *-lein* were repeated 12 times, the suffix *-isch* 14 times, and the suffix *-ling* 10 times. Non-suffixed nonword primes were created using the target word as a stem (e.g., *fille*) and a non-morphemic letter-sequence (e.g., *-ache*), which in combination with the stem resulted in a nonword (*fillache*). Unrelated primes were non-affixed nonwords that were orthographically unrelated to the target. All nonwords contained orthographically legal letter combinations and were pronounceable. Within each language, the items in the four prime conditions were matched on length.

For the purpose of the lexical decision task, 98 French nonword targets (48 for the prefixed materials and 48 for the suffixed materials) and 98 German nonword targets (48 for the prefixed materials and 48 for the suffixed materials) were created from words by replacing one or two letters (e.g., *brader* [to flog something] -> **brager*). In both the prefixed and suffixed materials, nonword targets were matched to real word targets on length. To mimic the structure of the primes preceding real word targets, primes preceding nonword targets were constructed in a similar fashion. Each nonword target was preceded by four different types of primes: primes that consisted of the nonword targets and the affix used in the affixed word condition (e.g., *rebrager-BRAGER*), primes that consisted of the nonword targets and the affix used in the affixed nonword condition (e.g., *exbrager-BRAGER*), primes that consisted of the nonword targets and the non-morphemic letter sequence used in the non-affixed nonword condition (e.g., *febrager-BRAGER*), and primes that consisted of a nonword the non-morphemic letter sequence used in the unrelated condition (e.g., *feminder-BRAGER*).

Procedure

On each trial, a 500-ms forward mask consisting of hash keys was presented first, followed by a 50-ms prime in lowercase letters, followed by the target in uppercase letters. Participants were instructed to decide if the presented item was a real word or a nonword. The target remained present until a response was made or until 60 seconds elapsed. Participants were instructed to respond as quickly and as accurately as possible. Each component of the experiment (prefixed and suffixed) took about 10 minutes to complete (i.e., approx. 20 minutes per participant). The experiment formed part of a longer longitudinal study and a number of other tasks were administered between the two testing components. To ensure that every participant saw every target only once, we created four counterbalanced experimental lists. An equal number of participants were assigned to each list. The word and nonword items were presented in randomized order. Moreover, the order of trial presentation within each list was randomized for each participant. Six practice items consisting of both words and nonwords were presented prior to the experimental trials.

In addition, children’s reading fluency was assessed using the 1-min-reading test (Gentaz, Sprenger-Charolles, & Theurel, 2015) in French, and the SLRT II reading test (Moll & Landerl, 2010) in German. The 1-min-reading and SLRT reading tests involved reading aloud a list of words and a list of nonwords. Based on each sample, we calculated a z-score for correctly read words and a z-score for correctly read nonwords. The average of the two scores was used as an index of reading ability in the analyses. Each child was assessed twice: once in Grade 3 and once in Grade 4.

Results

Analyses were performed using (generalized) linear mixed-effects models (Baayen, Davidson, & Bates, 2008) as implemented in the *lme4* package (Version 1.1-21; Bates, Maechler, Bolker, & Walker, 2015) in the statistical software R (Version 3.6.0, 2019-07-05, “Planting of a Tree”, RCoreTeam, 2019). RTs were log transformed to normalize residuals and were then analyzed using a linear mixed-effects (LME) model. For the error analysis, a generalized linear mixed-effects (GLME) model was created using logit transformation and a binomial link function. The significance of the fixed effects was determined with type III model comparisons using the *Anova* function in the *car* package (Version 3.0-3; Fox & Weisberg, 2019). Post hoc comparisons were carried out using cell means coding and single *df* contrasts with the *glht* function of the *multcomp* package (Version 1.4-10; Hothorn, Bretz, & Westfall, 2008) using the normal distribution to evaluate significance. Factor Prime Type was decomposed into three individual contrasts to determine the contribution of (i) embedded word processing, (ii) morpho-orthographic processing, and (iii) morpho-semantic processing. The first contrast was used to examine the influence of embedded word processing on the masked priming data, by comparing the non-affixed condition against the unrelated control condition. The second contrast was used to investigate the influence of morpho-orthographic processing on masked priming, by comparing the affixed nonword condition against the non-affixed nonword condition. The third contrast was used to explore the influence of morpho-semantic processing on masked priming, by comparing the affixed word against the affixed nonword condition.

Reaction Times

The French target word *lever* was mistakenly repeated and therefore removed.[4] Outlier trimming was performed separately within each grade. First, incorrect responses to nonwords (12.2% of the Grade 3 data; 9.7% of the Grade 4 data) were removed. Then, latencies below 300 or above 8000 ms were considered as extreme values and were also removed (1.1% of the Grade 3 data; 0.9% of the Grade 4 data). A base model, including only participants and items as random intercepts, was fitted to the data and data points with residuals exceeding 2.5 *SD*s were removed, following the procedure outlined by Baayen and Milin (2010; 2.2% of the Grade 3 data; 2.2% of the Grade 4 data). The LME model included the effect-coded fixed effects of Affix Type (Prefix, Suffix), Prime Type (Affixed Word, Affixed Nonword, Non-affixed Nonword, Unrelated), Language (French, German), Grade (Grade 3 vs. Grade 4) and Reading Fluency (standardized

---

[4] Six French items with orthographic illegalities (*inborder, inpasser, inplacer, inmontrer, inmouler, inménager*) were mistakenly included in the current set of materials. We therefore re-ran the analyses, which showed that the exclusion of these items did not change the direction or significance of the results.

score in each grade), and their interactions. Trial Order (standardized) was included as a covariate to control for task effects such as fatigue or habituation. Random intercepts and random slopes for the effect of Prime Type were used for both participants and items. Mean model RTs are displayed in Figures 2 and 3. The full model output, including all main effects and interactions, is provided in Appendix B.

There was a significant main effect of Grade ($\chi^2(1) = 3880.50$, $p < .001$), showing that fourth graders responded overall faster than third graders. There was also a significant main effect of Affix Type ($\chi^2(1) = 41.20$, $p < .001$), showing that children responded overall faster to suffixed than prefixed trials. The interaction between Affix Type and Grade was significant ($\chi^2(1) = 6.45$, $p = .011$), indicating that the Grade effect was larger for suffixes ($z = 46.51$, $p < .001$) than for prefixes ($z = 41.80$, $p < .001$). The interaction between Affix Type and Language was significant ($\chi^2(1) = 18.58$, $p < .001$), because the effect of Affix Type was significant in French ($z = 7.56$, $p < .001$), but not in German ($z = 1.50$, $p = .135$). The interaction between Grade and Language was significant ($\chi^2(1) = 88.98$, $p < .001$), because the effect of Grade was larger in German ($z = 48.50$, $p < .001$) than in French ($z = 39.27$, $p < .001$).

Priming Effects

There was a significant main effect of Prime Type ($\chi^2(3) = 66.18$, $p < .001$)[5]. Contrast coding revealed a significant effect of embedded word priming ($\Delta = 49$ ms, $z = 2.82$, $p = .005$), and a significant effect of morpho-orthographic priming ($\Delta = 17$ ms, $z = 2.15$, $p = .032$). The effect of morpho-semantic priming was not significant ($\Delta = 4$ ms, $z = 1.48$, $p = .139$). Crucially,

---

[5] The analyses focus on the description of our key priming effects, which were 1) embedded word priming, 2) morpho-orthographic priming, and 3) morpho-semantic priming. Therefore, the simple contrasts between the affixed conditions and the unrelated condition are not reported below. We note however, that these simple priming effects were highly significant in both French (affixed word vs. unrelated: $z = 5.39$, $p < .001$; affixed nonword vs. unrelated: $z = 5.21$, $p < .001$) and German (affixed word vs. unrelated: $z = 4.69$, $p < .001$; affixed nonword vs. unrelated: $z = 4.48$, $p < .001$).

the 3-way interaction between Prime Type, Affix Type and Language was significant ($\chi^2(3) = 9.02$, $p = .029$), suggesting that priming effects were modulated by differences between participant cohorts and item sets.

To follow up the 3-way interaction between Prime Type, Affix Type, and Language, contrast coding was used to analyse priming effects separately for prefixes and suffixes, and for each language group. A summary of the individual priming effects and effect sizes is presented in Table 3. Robust embedded word priming effects were observed in both languages, independently of affix type. In the German cohort, morpho-orthographic and morpho-semantic priming effects were entirely absent (see Table 3). In the French cohort, an interesting dissociation was observed between affix types. For prefixes, a significant effect of morpho-orthographic priming was observed ($\Delta = 43$ ms, $z = 3.19$, $p = .001$), while the effect of morpho-semantic priming was not significant ($\Delta = -24$ ms, $z = 1.44$, $p = .151$). For suffixes, there was a significant effect of morpho-semantic priming ($\Delta = 27$ ms, $z = 2.07$, $p = .038$), but the effect of morpho-orthographic priming was not significant ($\Delta = 2$ ms, $z = 0.89$, $p = .373$).

Individual Differences in Reading Fluency

There was a significant main effect of Reading Fluency ($\chi^2(1) = 188.02$, $p < .001$), indicating that children with high reading proficiency responded faster than children with low reading proficiency. The interaction between Affix Type and Reading Fluency was significant ($\chi^2(1) = 24.35$, $p < .001$), showing that the effect of Affix Type decreased with increasing reading proficiency. There was also a significant interaction between Grade and Reading Fluency ($\chi^2(1) = 181.96$, $p < .001$), indicating that the effect of reading proficiency was larger in Grade 3 than in Grade 4. The interaction between Language and Reading Fluency was also significant ($\chi^2(1) = 58.56$, $p < .001$), indicating that in the low reading proficiency range, French children responded faster than German children, but in the high reading proficiency range, German children responded faster than French children. In addition, the 3-way interaction between Affix Type, Language and Reading Fluency was significant ($\chi^2(1) = 38.11$, $p < .001$), because the Affix Type by Reading Fluency was significant in French ($z = 8.41$, $p < .001$), but not in German ($z = 0.83$, $p = .205$). The 3-way interaction between Grade, Language and Reading Fluency was also significant ($\chi^2(1) = 18.79$, $p < .001$), because the Grade by Reading Fluency interaction was larger in German ($z = 12.01$, $p < .001$) than in French ($z = 6.83$, $p < .001$).

Most importantly, the factor Prime Type was modulated by individual differences in reading fluency (see Figure 4). There was a significant three-way interaction between Prime Type, Language and Reading Fluency ($\chi^2(3) = 9.03$, $p = .029$), because individual differences in reading fluency differently affected priming in French children compared to German children. In French children, morpho-orthographic priming effects were modulated by reading fluency ($z = 3.33$, $p < .001$), with larger priming effects being observed in children with lower levels of reading fluency (see left panel of Figure 4). Morpho-semantic priming effects were also modulated by reading fluency ($z = 2.16$, $p = .031$), but here French children with lower levels of reading fluency showed a larger inhibitory morpho-semantic priming effect. Embedded word priming effects were not modulated by individual differences in reading fluency in French children ($z = 0.70$, $p = .486$). In contrast, in the German data, none of the priming effects were modulated by reading fluency (all $p >.1$; see right panel of Figure 4).

Accuracy

The GLME model included the same fixed effects, random effects and interactions as the LME model, except that we had to exclude the random intercepts and random slopes for the effect of Prime Type for participants and items, because the model did not converge. The mean model error rates are displayed in Figures 5 and 6. The detailed model output is provided in Appendix B.

The accuracy data showed a similar numerical trend as the RTs, suggesting that there was no speed-accuracy trade-off. There was a significant main effect of Grade ($\chi^2(1) = 78.09$, $p < .001$), showing that fourth graders responded overall more accurately than third graders. There was also a significant main effect of Language ($\chi^2(1) = 4.19$, $p = .041$), such that French children responded overall more accurately than German children. The interaction between Affix Type and Grade was significant ($\chi^2(1) = 5.11$, $p = .024$), reflecting the fact that the Grade effect was larger for prefixes ($z = 8.23$, $p < .001$) than suffixes ($z = 4.46$, $p < .001$). The interaction between Language and Grade was also significant ($\chi^2(1) = 24.36$, $p < .001$), because the Grade effect was larger in French ($z = 9.64$, $p < .001$) than in German ($z = 2.79$, $p = .005$).

Priming Effects

There was a significant main effect of Prime Type ($\chi^2(3) = 10.68$, $p = .014$), showing that the global difference between conditions was significant. However, none of the three contrasts were significant (embedded word priming: $z = 1.14$, $p = .253$; morpho-orthographic priming: $z = 0.36$, $p = .718$; morpho-semantic priming: $z = 1.74$, $p = .082$).

Individual Differences in Reading Fluency

There was a significant main effect of Reading Fluency ($\chi^2(1) = 122.73$, $p < .001$), indicating that children with high reading proficiency responded more accurately than children with low reading proficiency. The interaction between Language and Reading Fluency was significant ($\chi^2(1) = 12.41$, $p < .001$), suggesting that the effect of reading fluency was larger in German than in French.

Discussion

The aim of the present study was to shed light on the use of morphological knowledge during reading development, and to compare the developmental trajectories in two different languages. To this end, we carried out a two-year longitudinal masked priming study in two large cohorts of French and German speaking third- and fourth-graders. The study was designed in a way that it allowed for the dissociation of embedded word activation, morpho-orthographic and morpho-semantic processing, using four priming conditions: affixed word (*farmer-FARM*), affixed nonword (*farmity-FARM*), non-affixed nonword (*farmald-FARM*), and unrelated control primes (*workald-FARM*). In addition, to examine differences between prefix and suffix processing in children's reading development, the materials included half prefixed and half suffixed word and nonword trials. The study revealed several key findings, which are summarised below.

Embedded Word Priming

One of the first points to note is that the results showed robust embedded word priming effects that were stable across languages, grades, and affix types. These priming effects suggest that third- and fourth-graders are already able to activate words embedded in initial and final string positions, independently of whether they are accompanied by a real affix or a non-affix. These findings converge with prior evidence from skilled readers (e.g., Beyersmann et al., 2016; Beyersmann et al., 2018; Crepaldi, Rastle, Davis, & Lupker, 2013; Heathcote et al., 2018). One mechanism by which readers identify embedded words in initial and final string position is edge-aligned encoding of letter position, using the spaces at each end of the letter string as anchor points for positional, orthographic encoding (Beyersmann & Grainger, in press; Fischer-Baum et al., 2011; Grainger & Beyersmann, 2017). Significant embedded word priming has been previously reported for words embedded in edge-aligned string position (e.g., *bookpime-BOOK*), but not for words embedded in mid (e.g., *pibookme-BOOK*) or outer string position (e.g., *bopimeok-BOOK*), supporting the idea that words embedded in edge-aligned position receive the strongest form of lexical activation (Beyersmann et al., 2018). As such, the activation of embedded words can be achieved on the basis of an entirely non-morphological process of mapping letters onto existing whole-word representations in the orthographic lexicon, which is consistent with Grainger and Beyersmann's "word and affix" model (Beyersmann & Grainger, in press; Grainger & Beyersmann, 2017).

Cross-Linguistic Differences in Morphological Priming

Clearly distinct patterns of morpho-orthographic and morpho-semantic priming were observed across the two languages. In the German cohort, morpho-orthographic and morpho-semantic priming effects were entirely absent. In contrast, the French data revealed significant effects of morpho-orthographic and morpho-semantic priming that were modulated by individual differences in reading fluency and affix type. The interaction between Prime Type and Affix Type showed that, although the activation of embedded words played an equally important role in both prefixed and suffixed trials, it was only in the prefixed trials that French participants additionally benefitted from decomposition into morpho-orthographic subunits, whereas in the suffixed trials, the only additional benefit was from morpho-semantic overlap between prime and target. One explanation for the application of a more form-based segmentation mechanism for prefixes than for suffixes is that participants relied on a left-to-right decoding mechanism. Left-to-right reading techniques are not uncommon in children who are still in the earlier stages of learning to read (e.g., Acha & Perea, 2008; Ziegler, Perry, Ma-Wyatt, et al., 2003). When primes consisted of a prefix, children likely decoded the left aligned prefix first, and subsequently the right-aligned stem, which must have helped them gain faster access to the morpho-orthographic representations of prefixed words. When primes consisted of a suffix, children likely decoded the left aligned stem first, and then the right-aligned suffix, thus resulting in a slower, more semantically driven segmentation process.

One may ask why the application of a left-to-right scanning mechanism was not also reflected in larger priming effects for stems embedded in initial string position compared to stems embedded in final string position. In line with the principles of the “word and affix” model (Beyersmann & Grainger, in press; Grainger & Beyersmann, 2017), we hypothesize that the activation of embedded words and suffixes are based on two distinct processes. Embedded words can be activated via the embedded whole-word pathway, whereas affixes are subject to affix activation and morpho-orthographic full decomposition. The earlier acquisition of the embedded word activation mechanism leads to more efficient mappings between the orthographic input level and the orthographic lexicon, such that the activation of embedded words can rapidly proceed for words embedded in both initial and final string position. As a result, the activation of embedded words is less affected by a left-to-right scanning strategy. In contrast, the careful sequential scanning of letters would be of greater importance for the activation of comparatively weaker affix representations in children’s orthographic lexicon. These findings suggest that morphological processing in French primary school children must be driven by different component processes than in German primary school children and shows that the development of morphological processing mechanisms is influenced by the intrinsic linguistic properties of the language that children are exposed to.

Morphological Priming as a Function of Individual Differences in Reading Fluency

In the German cohort, the priming effects were not modulated by individual differences in reading fluency (but see Hasenäcker et al., 2020, who reported an effect of reading proficiency on masked priming latencies, with greater embedded word priming effects in good vs. poor German 2-4 graders). In the French cohort, two interesting interactions were observed between reading fluency and morphological priming. First, morpho-orthographic priming effects were modulated by reading fluency, with larger facilitatory priming effects in children with lower levels of reading fluency (see black dotted line in left panel of Figure 4). Second, morpho-semantic priming effects were modulated by reading fluency, with larger inhibitory priming effects in children with lower levels of reading fluency (see grey dotted line in left panel of Figure 4). A potential explanation for the modulation of morphological priming by children's individual differences in reading fluency is that French children at the lower end of the reading fluency spectrum must rely more heavily on morpho-orthographic segmentation processes (for a similar pattern of findings, see Beyersmann, Casalis, Ziegler, & Grainger, 2015; Beyersmann, Grainger, et al., 2015). French children with higher reading proficiency, on the other hand, were more expert at decomposing letter strings into morpho-semantic reading units. As has been previously argued by Beyersmann, Casalis, et al. (2015), participants with higher levels of language proficiency tend to map sub-lexical orthography onto whole-word orthographic representations, and therefore rely to a lesser extent on form-based morphological segmentation processes. In other words, good readers are able to rapidly access the lexical representations that are associated with the input string, thus gaining faster access to the semantics of the embedded morphemes, which would explain why increased morpho-semantic priming was observed in this participant group. This also provides an explanation for the inhibitory pattern of morpho-orthographic priming pattern in highly fluent readers, given the semantic incompatibility of the morphemic sub-units in this condition. Poorer readers, on the other hand, would be more likely to compensate for their less efficient whole-word activation by relying to a greater extent on morpho-orthographic segmentation.

Another point to note is that morpho-semantic priming (defined by the difference in priming between *farmer-FARM* and *farmity-FARM*), but not embedded word priming (defined by the difference in priming between *farmald-FARM* and *walkald-FARM*), was modulated by individual differences in reading fluency in the French cohort. This indicates that proficient French readers were able to access whole-word representations (as evidenced by increased priming in the *farmer-FARM* compared to the *farmity-FARM* condition). However, the lack of an interaction between embedded word priming and individual differences in reading fluency suggests that they did not stand out in their ability to identify embedded word units. The combination of these two findings shows that proficient developing readers of French are better at rapidly activating complex whole-word representations and their associated higher-level semantic representations, whereas less proficient readers make more use of lower-level form-based decoding stages.

Developmental Aspects of Complex Word Recognition

While German children primarily relied on one single mechanism (embedded word activation), French children used three clearly distinct mechanisms to process morphologically complex words (embedded word activation, morpho-orthographic processing, and morpho-semantic processing). Here we discuss how the “word and affix” model of complex word reading (Beyersmann & Grainger, in press; Grainger & Beyersmann, 2017) can account for these findings. The dissociation between embedded word activation and morphological segmentation effects provides support for the notion that embedded stem activations are handled via an independent pathway. Embedded stems, which also typically act as free-standing words in children’s reading (with the exception of bound stems), do not require setting up any specialized morphological representations. Children therefore quickly acquire the ability to match the orthographic input with existing whole-word orthographic representations, which includes the activation of embedded words that only form a subset of the letters of the input string. The activation of embedded words then acts as a bootstrapping mechanism for morphological parsing in children’s reading development (Beyersmann & Grainger, in press; Beyersmann, Grainger, et al., 2019; Grainger & Beyersmann, 2017). To become proficient at applying more sophisticated morpho-orthographic and morpho-semantic processes, children need to first acquire abstract affix representations. The model therefore predicts a number of consecutive developmental stages, which children have to go through in order to read complex words fluently. The developmental milestones in this process include the acquisition of an embedded word activation mechanism, followed by the acquisition of a morpho-semantic feedback mechanism, followed by the development of a morpho-orthographic full decomposition mechanism (Beyersmann & Grainger, in press; Grainger & Beyersmann, 2017).

Our results provide insights into the developmental trajectory of morphological parsing mechanisms across two different languages. In German, the prominence of embedded word priming effects suggests that children in this cohort had not yet moved past the initial developmental stage of embedded word activation. This finding is not entirely surprising, given that the German language is characterized by a productive compounding system (e.g., Creutz & Lagus, 2005; Creutz et al., 2005; Fleischer & Barz, 1995; Meyer, 1993). Due to the frequency of exposure to stem-stem concatenations, German speakers are likely to develop a high level of proficiency in processing embedded words (Beyersmann et al., 2020). The absence of morpho-orthographic or morpho-semantic priming effects in German children confirms the hypothesis that embedded word activation represents the primary word identification mechanism in the developing German reading system. Our data do not answer the question of whether German children ever move past the initial stage of embedded word activation. They may continue to use embedded word activation as a primary tool to process complex words once they have become skilled readers. We know, however, from previous work, that in contrast to children, German speaking adults do show evidence for morpho-orthographic decomposition, in addition to embedded word processing (Hasenäcker et al., 2016). This implies that German children, on their path to becoming skilled readers, do indeed develop morphological segmentation mechanisms that go beyond the early stage of embedded word activation, but that this does not happen until the later stages of primary school.

The masked priming effects in the French data show that children in this cohort, although matched to their German peers in age and grade-level, have already acquired the ability to rapidly decompose letter strings into morpho-orthographic and morpho-semantic sub-units by Grade 3. These findings converge with the results of Quémart et al. (2011), suggesting that morpheme segmentation mechanisms are acquired relatively early in French children's reading development. Grainger and Beyersmann's model predicts that in order to reach a level of automaticity in morpho-orthographic processing, children must sequentially move through the earlier developmental stages of embedded word activation and morpho-semantic processing. The model thus implies that French children move through the developmental stages faster and acquire the skill to rapidly and automatically decompose letter strings into their morphemes sooner in reading development than German children. There are two explanations for why this may be the case. One explanation for why morphological processing may be of greater importance in a language like French is that the primary word formation process is one that includes the concatenation of stems and affixes. The segmentation into stem + affix provides an avenue for rapid access to the meaning of the embedded constituents and can also be used as a tool to derive meaning from novel words with morphologically complex structures.

An alternative explanation for why French children acquire morphological segmentation mechanisms early in their reading development is that the nature of French orthography induces processing mechanisms that are more likely to pick up sub-lexical reading units. French orthography is high in complexity, due to its large number of complex letter-sound correspondences (e.g., Schmalz et al., 2016; Schmalz et al., 2015; van den Bosch et al., 1994), including many multi-letter rules and context-sensitive regularities. Importantly, French is orthographically more complex than German (De Simone et al., under review; Schmalz et al., 2016). When words contain complex correspondences, the identification of sub-lexical reading units is necessary to access full information about the word's phonology and semantics. Therefore, learning to read within a complex orthography may shift children's reliance from single letter decoding onto multi-letter decoding early on in reading development. The complexity of the French orthography thus provides another possible explanation for the earlier acquisition of morphological segmentation mechanisms in French compared to German children.

Limitations and Future Directions

A point that potentially raises concern is that the observed embedded word priming effects may be attributed to the orthographic overlap between prime and target, and to principles of letter position encoding, rather than the activation of the embedded word as a lexical unit. However, what speaks against the argument of lower-level orthographic processing is that the activation of embedded words is known to be modulated by morphological family size (Beyersmann & Grainger, 2018) and conditional suffix probability of the embedded word unit

(Grainger & Beyersmann, 2020), suggesting that embedded words are indeed activated to the level of the lexicon. Moreover, the here reported evidence for morphological processing in the French sample demonstrates that the observed priming effects, at least in the French sample, were not just a result of the orthographic similarity between primes and targets, but rather due to the complex interplay between embedded word and morpheme activation mechanisms. An interesting follow up of the present study would be the cross-linguistic examination of conditional suffix probability effects in German and French speaking children, as a direct test of the lexical mechanisms underlying embedded word processing. The here observed differences in morphological processing between German and French make the prediction that effects of conditional suffix probability should develop sooner in French compared to German speaking children.

Due to the tightly controlled experimental design, the German and French materials were restricted to verb targets in the prefixed set and noun/adjective targets in the suffixed set. It is possible that the differences in syntactic word class contributed to the observed differences between prefixed and suffixed priming in the French sample. Therefore, a broader investigation of morphological priming across a wider range of syntactic word classes in future research would be desirable.

From a broader developmental perspective, it is important to be reminded that the present study's methodological approach, that is, masked priming, provides insights into the rapid, more form-based aspects of morphological processing and does not necessary reflect the entire chain of processes that are activated during visual word recognition and - more generally - during reading acquisition. To understand the influence of morphological knowledge on children's reading skills, a wider range of methods should be used, perhaps with longer prime durations, to investigate the later stages of the reading process, as well as paradigms that would allow us to examine morphological processing across modalities. Related to this, a recent lexical decision study with adults showed that morphological processing may be more prominent in the visual than in the auditory modality (Beyersmann et al., 2020), but this has yet to be confirmed with children.

A further limitation concerns the fact that the current cross-linguistic investigation was based on the comparison of two languages that not only differ with respect to their productivity of morphological word formation processes (i.e., more productive compounding in German than in French), but also in terms of orthographic complexity (i.e., more complex letter-sound correspondences in French than in German). It is therefore impossible to clearly tease apart the linguistic pre-requisites that may affect how children learn to read complex words within each of these languages. To gain a deeper understanding of how language-specific differences in orthography and morphology might influence reading acquisition, we need to build on the present study to investigate morphological processing within a broader, universal context. Effects of visual word recognition need to be studied by considering the "full linguistic environment" of a particular language (Frost, 2012), including phonology, orthography, morphology, and semantics, rather than just taking into account one or the other. For instance, in Hebrew, the letters of stem morphemes are not represented consecutively, whereas in most Indo-European languages they are. This is just another example of how the complex interplay between orthography, morphology and semantics imposes processing constraints that vastly differ across languages. Hence, cross-linguistic investigations are in a unique position to shed light onto how statistical properties of different writing systems might influence the development of complex word reading mechanisms in young children, and therefore represent a powerful empirical tool for future research.

Acknowledgements

This research was supported by grants from the French National Agency for Research (ANR) and the German Research Foundation (DFG), in particular the French-German ANR/DFG grant scheme in social sciences and humanities (ANR-15-FRAL-0003-01) and a DFG grant (SCHR-1268/2–1). The research also benefitted from support from grants ANR-16-CONV-0002, ANR-11-LABX-0036). EB was supported by a Discovery Early Career Researcher Award (DECRA) by the Australian Research Council (DE190100850), and JG by ERC grant 742141.

References

Acha, J., & Perea, M. (2008). The effects of length and transposed-letter similarity in lexical decision: evidence with beginning, intermediate, and adult readers. *British Journal of Psychology, 99*, 245-264.

Amenta, S., & Crepaldi, D. (2012). Morphological processing as we know it: an analytical review of morphological effects in visual word identification. *Frontiers in Psychology, 3*, 1-12.

Aro, M., & Wimmer, H. (2003). Learning to read: English in comparison to six more regular orthographies. *Applied Psycholinguistics, 24*, 621-635.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*, 390–412.

Baayen, R. H., & Milin, P. (2010). Analyzing reaction times. *International Journal of Psychological Research, 3*, 12–28.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. . *Journal of Statistical Software, 67*, 1-48. doi:http://dx.doi.org/10.18637/jss.v067.i01

Beyersmann, E., Bolger, D., Pattamadilok, C., New, B., Ziegler, J. C., & Grainger, J. (2019). Morphological processing without semantics: An ERP study with spoken words. *Cortex, 116*, 55-73.

Beyersmann, E., Casalis, S., Ziegler, J. C., & Grainger, J. (2015). Language proficiency and morpho-orthographic segmentation. *Psychonomic Bulletin & Review, 22*, 1054–1061.

Beyersmann, E., Castles, A., & Coltheart, M. (2012). Morphological processing during visual word recognition in developing readers: Evidence from masked priming. *The Quarterly Journal of Experimental Psychology, 65*(7), 1306–1326.

Beyersmann, E., Cavalli, E., Casalis, S., & Colé, P. (2016). Embedded Stem Priming Effects in Prefixed and Suffixed Pseudowords. *Scientific Studies of Reading, 20*(3), 220-230. doi:10.1080/10888438.2016.1140769

Beyersmann, E., & Grainger, J. (2018). Support from the morphological family when unembedding the stem. *Journal of Experimental Psychology: Learning, Memory and Cognition, 44*(1), 135-142.

Beyersmann, E., & Grainger, J. (in press). The role of embedded words and morphemes in reading. In D. Crepaldi (Ed.), *Current Issues in the Psychology of Language*. Hove: Psychology Press.

Beyersmann, E., Grainger, J., Casalis, S., & Ziegler, J. C. (2015). Effects of reading proficiency on embedded stem priming in primary school children. *Journal of Experimental Child Psychology, 139*, 115-126.

Beyersmann, E., Grainger, J., & Castles, A. (2019). Embedded stems as a bootstrapping mechanism for morphological parsing during reading development. *Journal of Experimental Child Psychology, 182*, 196-210. doi:10.1016/j.jecp.2019.01.010

Beyersmann, E., Kezilas, Y., Coltheart, M., Castles, A., Ziegler, J. C., Taft, M., & Grainger, J. (2018). Taking the book from the bookshelf: Masked constituent priming effects in compound words and nonwords. *Journal of Cognition, 1*(1), 1-10.

Beyersmann, E., Mousikou, P., Javourey-Drevet, L., Schroeder, S., Ziegler, J. C., & Grainger, J. (2020). Morphological processing across modalities and languages. *Scientific Studies of Reading, 24*(6), 500-519.

Beyersmann, E., Ziegler, J. C., & Grainger, J. (2015). Differences in the processing of prefixes and suffixes revealed by a letter-search task. *Scientific Studies of Reading, 19,* 360-373.

Casalis, S., Quemart, P., & Duncan, L. G. (2015). How language affects children's use of derivational morphology in visual word and pseudoword processing: evidence from a cross-language study. *Front Psychol*, *6*, 452. doi:10.3389/fpsyg.2015.00452

Crepaldi, D., Rastle, K., Davis, C. J., & Lupker, S. J. (2013). Seeing Stems Everywhere: Position-Independent Identification of Stem Morphemes. *Journal of Experimental Psychology: Human Perception and Performance, 39*(2), 510-525.

Creutz, M., & Lagus, K. (2005). Unsupervised morpheme segmentation and morphology induction from text corpora. In *Technical Report No. A81*. Helsinki University of Technology, Espoo: Laboratory of Computer and Information Science.

Creutz, M., Lagus, K., Lindén, K., & Virpioja, S. (2005). *Morfessor and hutmegs: Unsupervised morpheme segmentation for highly-inflecting and compounding languages.* Paper presented at the Proceedings of the 2nd Baltic Conference on Human Language Technologies, Tallinn.

Dawson, N., Rastle, K., & Ricketts, J. (2018). Morphological effects in visual word recognition: Children, adolecents, and adults. *Journal of Experimental Psychology: Learning, Memory and Cognition, 44*(4), 645–654. doi:10.1037/xlm0000485

De Simone, E., Beyersmann, E., Mulatti, C., Mirault, J., & Schmalz, X. (under review). Order among chaos: Cross-linguistic differences and developmental trajectories in pseudoword reading aloud using pronunciation Entropy. *PLoS ONE*.

Fischer-Baum, S., Charny, J., & McCloskey, M. (2011). Both-edges representation of letter position in reading. *Psychonomic Bulletin & Review, 18*(6), 1083-1089. doi:10.3758/s13423-011-0160-3

Fleischer, W., & Barz, I. (1995). *Wortbildung der deutschen Gegenwartssprache*. Tübingen, Germany: Niemeyer.

Forster, K. I. (1987). Form priming with masked primes: The best match hypothesis. In M. Coltheart (Ed.), *Attentionand performance XII: The psychology of reading*. Hillsdale, NJ: Erlbaum.

Forster, K. I., & Veres, C. (1998). The prime lexicality effect: Form-priming as a function of prime awareness, lexical status, and discrimination difficulty. *Journal of Experimental Psychology: Learning, Memory and Cognition, 24*(2), 498-514.

Fox, J., & Weisberg, S. (2019). *An R companion to applied regression (2nd ed.)* Thousand Oaks, CA: Sage.

Frost, R. (2012). Towards a universal model of reading. *Behavioral and Brain Sciences, 35*, 263-279.

Gentaz, E., Sprenger-Charolles, L., & Theurel, A. (2015). Differences in the predictors of reading comprehension in first graders from low socio-economic status families with either good or poor decoding skills. *PLoS ONE*, *10*.

Giraudo, H., & Voga, M. (2016). Words matter more than morphemes: An investigation of masked priming effects with complex words and non-words. *Italian Journal of Linguistics, 28*, 49–78.

Grainger, J., & Beyersmann, E. (2017). Edge-aligned embedded word activation initiates morpho-orthographic segmentation. In B. H. Ross (Ed.), *The Psychology of Learning and Motivation* (Vol. 67, pp. 285–317). San Diego, CA: Elsevier Academic Press.

Grainger, J., & Beyersmann, E. (2020). Effects of lexicality and pseudo-morphological complexity on embedded word priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, Advance online publication*.

Grainger, J., Colé, P., & Segui, J. (1991). Masked morphological priming in visual word recognition. *Journal of Memory and Language & Speech, 30*, 370–384.

Hasenäcker, J., Beyersmann, E., & Schroeder, S. (2016). Masked morphological priming in German-speaking adults and children: Evidence from response time distributions. *Frontiers in Psychology, 7*, 1-11. doi:10.3389/fpsyg.2016.00929

Hasenäcker, J., Beyersmann, E., & Schroeder, S. (2020). Morphological priming in children: Disentangling the effects of school-grade and reading skill. *Scientific Studies of Reading, 24*(6), 484-499.

Heathcote, L., Nation, K., Castles, A., & Beyersmann, E. (2018). Do 'blacheap' and 'subcheap' both prime 'cheap'? An investigation of morphemic status and position in early visual word processing. *Quarterly Journal of Experimental Psychology, 71*(8), 1645-1654.

Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous inference in general parametric models. *Biometrical Journal: Biometrische Zeitschrift, 50*, 346–363.

Juola, P. (1998). Measuring linguistic complexity: The morphological tier. *Journal of Quantitative Linguistics, 5*, 206–213. doi:https://doi.org/10.1080/09296179808590128

Juola, P. (2008). Assessing linguistic complexity. In M. Miestamo, K. Sinnemäki, & F. Karlsson (Eds.), *Language complexity: Typology, contact, change* (pp. 89–108). Amsterdam, The Netherlands: John Benjamins Publishing Company.

Kettunen, K. (2014). Can Type-Token Ratio be Used to Show Morphological Complexity of Languages? *Journal of Quantitative Linguistics, 21*(3), 223-245. doi:10.1080/09296174.2014.911506

Kim, S. Y., Wang, M., & Taft, M. (2015). Morphological decomposition in the recognition of prefixed and suffixed words: Evidence from Korean. *Scientific Studies of Reading, 19,* 183-203.

Lázaro, M., Acha, J., Rosa, S., García, S., & Sainz, J. (2016). Exploring the derivative suffix frequency effect in Spanish speaking children. *Reading and Writing, 1*(30), 163–185.

Lázaro, M., García, L., & Burani, C. (2015). How orthographic transparency affects morphological processing in young readers with and without reading disability. *Scandinavian Journal of Psychology, 56*(5), 498-507. doi:10.1111/sjop.12213

Lázaro, M., Illera, V., Acha, J., Escalonilla, A., García, S., & Sainz, J. S. (2018). Morphological effects in word identification: tracking the developmental trajectory of derivational suffixes in Spanish. *Reading and Writing, 31*(7), 1669-1684. doi:10.1007/s11145-018-9858-1

Lété, B., Sprenger-Charolles, L., & Colé, P. (2004). MANULEX: A grade-level lexical database from French elementary school readers. *Behavior Research Methods, Instruments, & Computers, 1*(36), 156-166.

Longtin, C. M., & Meunier, F. (2005). Morphological decomposition in early visual word processing. *Journal of Memory and Language, 53*, 26-41. Retrieved from <Go to ISI>://000229750700002

Longtin, C. M., Segui, J., & Hallé, P. A. (2003). Morphological priming without morphological relationship. *Language and Cognitive Processes, 18*(3), 313–334.

Meyer, R. (1993). *Compound comprehension in isolation and in context: The contribution of conceptual and discourse knowledge to the comprehension of German novel noun-noun compounds*. Tübingen, Germany: Niemeyer.

Moll, K., & Landerl, K. (2010). *SLRT-II: Lese- und Rechtschreibtest: Weiterentwicklung der Salzburger Lese- und Rechtschreibtests (SLRT): Manual*. Bern, Switzerland: Verlag Hans Huber.

Morris, J., Frank, T., Grainger, J., & Holcomb, P. J. (2007). Semantic transparency and masked morphological priming: an ERP investigation. *Psychophysiology, 44*, 506-521.

Mousikou, P., Beyersmann, E., Ktori, M., Javourey, L., Crepaldi, D., Ziegler, J. C., . . . S., S. (2020). Orthographic consistency influences morphological processing in reading aloud: Evidence from a cross-linguistic study. *Developmental Science, 23*(6), 1-19.

Mousikou, P., & Schroeder, S. (2019). Morphological processing in single-word and sentence reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 45*, 881–903.

Nicoladis, E., & Krott, A. (2007). Word family size and French-speaking children's segmentation of existing compounds. *Language Learning, 57*(2), 201-228.

Quémart, P., Casalis, S., & Colé, P. (2011). The role of form and meaning in the processing of written morphology: A priming study in French developing readers. *Journal of Experimental Child Psychology, 109*, 478-496.

Quémart, P., Casalis, S., & Duncan, L. G. (2012). Exploring the role of bases and suffixes when reading familiar and unfamiliar words: Evidence from French young readers. *Scientific Studies of Reading, 16*(5), 424–442.

Rastle, K. (2018). The place of morphology in learning to read in English. *Cortex*. doi:https://doi.org/10.1016/j.cortex.2018.02.008

Rastle, K., & Davis, M. H. (2008). Morphological decomposition based on the analysis of orthography. *Language & Cognitive Processes, 23*, 942-971.

Rastle, K., Davis, M. H., & New, B. (2004). The broth in my brother's brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin & Review, 11*, 1090-1098. Retrieved from <Go to ISI>://000227989700015

RCoreTeam. (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from https://www.R-project.org/

Rey-Debove, J. (1984). Le domaine de la morphologie lexicale [The domain of lexical morphology]. *Cahiers de Lexicologie, 45*, 3-19.

Roelcke, T. (1997). *Sprachtypologie des Deutschen: historische, regionale und funktionale Variation [Language typology of German: historical, regional, and functional variation]*. Berlin: de Gruyter.

Sadeniemi, M., Kettunen, K., Lindh-Knuutila, T., & Honkela, T. (2008). Complexity of European Union Languages: A comparative approach. *Journal of Quantitative Linguistics, 15*(2), 185-211. doi:10.1080/09296170801961843

Schiff, R., Raveh, M., & Fighel, A. (2012). The Development of the Hebrew Mental Lexicon: When Morphological Representations become Devoid of Their Meaning. *Scientific Studies of Reading, 16*(5), 383-403.

Schmalz, X., Beyersmann, E., Cavalli, E., & Marinus, E. (2016). Unpredictability and complexity of print-to-speech correspondences increase reliance on lexical processes: more evidence for the orthographic depth hypothesis. *Journal of Cognitive Psychology, 28*(6), 658-672. doi:10.1080/20445911.2016.1182172

Schmalz, X., Marinus, E., Coltheart, M., & Castles, A. (2015). Getting to the bottom of orthographic depth. *Psychonomic Bulletin and Review, 22*(6), 1614-1629. doi:10.3758/s13423-015-0835-2

Schroeder, S., Würzner, K. M., Heister, J., Geyken, A., & Kliegl, R. (2015). childLex: a lexical database of German read by children. *Behavior Research Methods, 47*(4), 1085-1094.

Taft, M. (2003). Morphological representation as a correlation between form and meaning. In E. Assink & D. Sandra (Eds.), *Reading complex words* (pp. 113-137). Amsterdam, The Netherlands: Kluwer.

Taft, M., & Forster, K. I. (1975). Lexical storage and retrieval of prefixed words. *Journal of Verbal Learning and Verbal Behavior, 14*, 638-647.

van den Bosch, A., Content, A., Daelemans, W., & de Gelder, B. (1994). Measuring the complexity of writing systems. *Journal of Quantitative Linguistics, 1*(3), 178–188.

Ziegler, J. C., Perry, C., & Coltheart, M. (2000). The DRC model of visual word recognition and reading aloud: An extension to German. *European Journal of Cognitive Psychology, 12*(3), 413–430.

Ziegler, J. C., Perry, C., & Coltheart, M. (2003). Speed of lexical and nonlexical processing in French: The case of the regularity effect. *Psychological Bulletin and Review, 10*(4), 947–953.

Ziegler, J. C., Perry, C., Ma-Wyatt, A., Ladner, D., & Schulte-Korne, G. (2003). Developmental dyslexia in different languages: Language-specific or universal? . *Journal of Experimental Child Psychology, 86*(3), 169-193. doi:10.1016/S0022-0965(03)00139-5

Appendix A. Items used in the study.

	French prefixed stimuli				
	affixed word prime	**affixed nonword prime**	**non-affixed nonword prime**	**unrelated prime**	**target**
1	déborder	inborder	daborder	dadurcir	BORDER
2	décoller	incoller	dacoller	dabrûler	COLLER
3	découper	incouper	dacouper	dacalmer	COUPER
4	découvrir	incouvrir	dacouvrir	dadiviser	COUVRIR
5	défaire	infaire	dafaire	damunir	FAIRE
6	défiler	infiler	dafiler	dagâter	FILER
7	démontrer	inmontrer	damontrer	dasecouer	MONTRER
8	démouler	inmouler	damouler	dafumer	MOULER
9	dépasser	inpasser	dapasser	dacocher	PASSER
10	déplacer	inplacer	daplacer	daisoler	PLACER
11	déménager	inménager	daménager	datraiter	MÉNAGER
12	déranger	inranger	daranger	daobéir	RANGER
13	endormir	bidormir	gidormir	gifilmer	DORMIR
14	enfermer	bifermer	gifermer	gicoudre	FERMER
15	enfoncer	bifoncer	gifoncer	gifendre	FONCER
16	enfuir	bifuir	gifuir	giagir	FUIR
17	enlever	bilever	gilever	gifinir	LEVER
18	enneiger	bineiger	gineiger	givibrer	NEIGER
19	entraîner	bitraîner	gitraîner	gidoucher	TRAÎNER
20	envoler	bivoler	givoler	gigarer	VOLER
21	encadrer	bicadrer	gicadrer	gicourir	CADRER
22	encercler	bicercler	gicercler	gigonfler	CERCLER
23	endurer	bidurer	gidurer	giskier	DURER
24	enlacer	dislacer	gilacer	gisucer	LACER
25	préchauffer	dischauffer	blochauffer	blohéberger	CHAUFFER
26	prélasser	dislasser	blolasser	blofriser	LASSER
27	prévenir	disvenir	blovenir	blologer	VENIR
28	prédire	disdire	blodire	blofier	DIRE
29	préjuger	disjuger	blojuger	blomêler	JUGER
30	prélever	dislever	blolever	blonager	LEVER
31	préoccuper	disoccuper	blooccuper	blogrogner	OCCUPER
32	préposer	biposer	bloposer	blorugir	POSER
33	prévoir	disvoir	blovoir	blorire	VOIR
34	prédominer	disdominer	blodominer	blohabiter	DOMINER
35	prédéterminer	disdéterminer	blodéterminer	blosommeiller	DÉTERMINER
36	préfigurer	disfigurer	blofigurer	blohériter	FIGURER
37	recharger	excharger	fecharger	felaisser	CHARGER
38	recopier	excopier	fecopier	feglacer	COPIER
39	redonner	exdonner	fedonner	fefâcher	DONNER
40	redresser	exdresser	fedresser	femaigrir	DRESSER

41	regagner	exgagner	fegagner	femarier	GAGNER
42	regarder	exgarder	fegarder	femoquer	GARDER
43	regrouper	exgrouper	fegrouper	femasquer	GROUPER
44	rejoindre	exjoindre	fejoindre	femuscler	JOINDRE
45	relire	exlire	felire	feoser	LIRE
46	remarquer	exmarquer	femarquer	fenourrir	MARQUER
47	remettre	exmettre	femettre	fecouler	METTRE
48	remonter	exmonter	femonter	feoffrir	MONTER

French suffixed stimuli

	affixed word prime	**affixed nonword prime**	**non-affixed nonword prime**	**unrelated prime**	**target**
1	sagesse	sagable	sagugne	mûrugne	SAGE
2	jeunesse	jeunable	jeunugne	ballugne	JEUNE
3	tristesse	tristable	tristugne	beurrugne	TRISTE
4	politesse	politable	politugne	durugne	POLI
5	princesse	princable	princugne	futurugne	PRINCE
6	richesse	richable	richugne	cannugne	RICHE
7	souplesse	souplable	souplugne	marinugne	SOUPLE
8	tendresse	tendrable	tendrugne	meublugne	TENDRE
9	tigresse	tigrable	tigrugne	cartugne	TIGRE
10	vieillesse	vieillable	vieillugne	carottugne	VIEILLE
11	faiblesse	faiblable	faiblugne	proprugne	FAIBLE
12	finesse	finable	finugne	fixugne	FINE
13	roulette	roulible	roulache	fablache	ROULE
14	poulette	poulible	poulache	fichache	POULE
15	cachette	cachible	cachache	doutache	CACHE
16	fillette	fillible	fillache	gommache	FILLE
17	bandelette	bandible	bandache	foirache	BANDE
18	bichette	bichible	bichache	genrache	BICHE
19	boulette	boulible	boulache	gravache	BOULE
20	casquette	casquible	casquache	piratache	CASQUE
21	chemisette	chemisible	chemisache	guitarache	CHEMISE
22	clochette	clochible	clochache	royalache	CLOCHE
23	feuillette	feuillible	feuillache	canichache	FEUILLE
24	maisonnette	maisonible	maisonache	secondache	MAISON
25	froideur	froidoir	froiduin	hiveruin	FROID
26	danseur	dansoir	dansuin	hainuin	DANSE
27	grandeur	grandoir	granduin	légeruin	GRAND
28	boxeur	boxoir	boxuin	rosuin	BOXE
29	grosseur	grossoir	grossuin	sombruin	GROSSE
30	largeur	largoir	larguin	huiluin	LARGE
31	voyageur	voyagure	voyaguin	clairuin	VOYAGE
32	douceur	douxoir	douxuin	noiruin	DOUX

33	joueur	jouoir	joueuin	saluin	JOUE
34	pêcheur	pêchoir	pêchuin	jaunuin	PÊCHE
35	hauteur	hautoir	hautuin	ronduin	HAUT
36	chasseur	chassoir	chassuin	douchuin	CHASSE
37	fraisier	fraisure	fraisule	cruchule	FRAISE
38	bananier	bananure	bananule	escalule	BANANE
39	dentier	dentoir	dentule	muetule	DENT
40	caissier	caissure	caissule	estimule	CAISSE
41	glacier	glacure	glacule	larmule	GLACE
42	poirier	poirure	poirule	luttule	POIRE
43	écolier	écolure	écolule	moulule	ÉCOLE
44	policier	policure	policule	foudrule	POLICE
45	saladier	saladure	saladule	gloirule	SALADE
46	voilier	voiloir	voilule	olivule	VOILE
47	pommier	pommure	pommule	ombrule	POMME
48	fermier	fermure	fermule	pellule	FERME

German prefixed stimuli

	affixed word prime	**affixed nonword prime**	**non-affixed nonword prime**	**unrelated prime**	**target**
1	aufrufen	hinrufen	karrufen	karlegen	RUFEN
2	auffangen	vorfangen	golfangen	golkennen	FANGEN
3	auflösen	hinlösen	karlösen	karmögen	LÖSEN
4	aufleben	hinleben	karleben	karmalen	LEBEN
5	auffüllen	hinfüllen	golfüllen	golhassen	FÜLLEN
6	aufhängen	vorhängen	karhängen	karplanen	HÄNGEN
7	aufheben	hinheben	golheben	golrasen	HEBEN
8	aufbleiben	hinbleiben	karbleiben	karbetteln	BLEIBEN
9	aufbrechen	hinbrechen	karbrechen	karflitzen	BRECHEN
10	aufblitzen	hinblitzen	karblitzen	karfechten	BLITZEN
11	auffordern	vorfordern	golfordern	golbreiten	FORDERN
12	auffressen	hinfressen	golfressen	golsperren	FRESSEN
13	mitessen	hinessen	golessen	golkauen	ESSEN
14	mithelfen	vorhelfen	golhelfen	golzerren	HELFEN
15	mitteilen	hinteilen	karteilen	karheizen	TEILEN
16	mitwirken	vorwirken	karwirken	karrühren	WIRKEN
17	mitsingen	hinsingen	golsingen	golsausen	SINGEN
18	mitkriegen	vorkriegen	karkriegen	karfliegen	KRIEGEN
19	mitfreuen	hinfreuen	karfreuen	karräumen	FREUEN
20	mitdenken	hindenken	kardenken	karhasten	DENKEN
21	mitmachen	hinmachen	golmachen	golgraben	MACHEN
22	mithören	vorhören	karhören	karsehen	HÖREN
23	mitlachen	vorlachen	karlachen	karlocken	LACHEN
24	mitspielen	hinspielen	karspielen	karsterben	SPIELEN

25	abbeißen	umbeißen	embeißen	emhüllen	BEIßEN
26	abfinden	umfinden	arfinden	arheulen	FINDEN
27	abholen	umholen	arholen	arbauen	HOLEN
28	abkaufen	umkaufen	emkaufen	emkehren	KAUFEN
29	ablehnen	zulehnen	arlehnen	arfassen	LEHNEN
30	ablesen	umlesen	emlesen	emwehen	LESEN
31	abreißen	zureißen	emreißen	emgießen	REIßEN
32	ablecken	umlecken	emlecken	emblasen	LECKEN
33	absuchen	umsuchen	arsuchen	arstehen	SUCHEN
34	abwarten	umwarten	emwarten	embinden	WARTEN
35	abtauchen	umtauchen	emtauchen	emwickeln	TAUCHEN
36	abstürzen	zustürzen	arstürzen	arbrüllen	STÜRZEN
37	anblicken	zublicken	arblicken	artreiben	BLICKEN
38	anführen	umführen	emführen	emnicken	FÜHREN
39	anklagen	zuklagen	arklagen	artrauen	KLAGEN
40	anhalten	umhalten	emhalten	emkochen	HALTEN
41	anlügen	zulügen	emlügen	ematmen	LÜGEN
42	anmerken	ummerken	armerken	arweinen	MERKEN
43	anbieten	umbieten	embieten	emsetzen	BIETEN
44	anpassen	umpassen	empassen	emtanzen	PASSEN
45	anweisen	umweisen	arweisen	arkosten	WEISEN
46	anfühlen	umfühlen	emfühlen	emkippen	FÜHLEN
47	anzeigen	zuzeigen	emzeigen	embeugen	ZEIGEN
48	anmelden	zumelden	armelden	arleihen	MELDEN

German suffixed stimuli

	affixed word prime	affixed nonword prime	non-affixed nonword prime	unrelated prime	target
1	brettchen	brettkeit	brettucht	bodenucht	BRETT
2	engelchen	engelkeit	engelnauf	berufnauf	ENGEL
3	kleidchen	kleidkeit	kleiducht	grunducht	KLEID
4	kerlchen	kerlkeit	kerltern	glastern	KERL
5	spielchen	spielkeit	spielnauf	honignauf	SPIEL
6	steinchen	steinkeit	steinucht	piratucht	STEIN
7	löffelchen	löffelkeit	löffelnauf	athletnauf	LÖFFEL
8	schildchen	schildkeit	schilducht	balkonucht	SCHILD
9	zettelchen	zettelkeit	zettelnauf	arbeitnauf	ZETTEL
10	frauchen	fraukeit	fraupern	wertpern	FRAU
11	pferdchen	pferdkeit	pferducht	naturucht	PFERD
12	tischchen	tischkeit	tischucht	blitzucht	TISCH
13	mangelhaft	mangelisch	mangelnauf	besuchnauf	MANGEL
14	herzhaft	herzling	herzucht	holzucht	HERZ
15	schmerzhaft	schmerzisch	schmerzucht	fahrraducht	SCHMERZ
16	zweifelhaft	zweifelisch	zweifeltern	teppichtern	ZWEIFEL
17	standhaft	standisch	standucht	reichucht	STAND

18	traumhaft	traumling	traumtern	fischtern	TRAUM
19	bildhaft	bildisch	bilducht	bettucht	BILD
20	ekelhaft	ekelisch	ekeltern	sinntern	EKEL
21	zwanghaft	zwangling	zwangucht	königucht	ZWANG
22	krampfhaft	krampfisch	krampfucht	fruchtucht	KRAMPF
23	scherzhaft	scherzling	scherznauf	rezeptnauf	SCHERZ
24	sprunghaft	sprungling	sprungucht	schiffucht	SPRUNG
25	buntheit	buntlein	buntucht	naivucht	BUNT
26	freiheit	freilein	freitern	langtern	FREI
27	krankheit	kranklein	krankucht	aktivucht	KRANK
28	schönheit	schönlein	schönpern	fabelpern	SCHÖN
29	wahrheit	wahrlein	wahrnauf	hemdnauf	WAHR
30	offenheit	offenlein	offenucht	flittucht	OFFEN
31	klugheit	kluglein	klugnauf	mundnauf	KLUG
32	stummheit	stummlein	stummtern	kreuztern	STUMM
33	dummheit	dummlein	dummtern	formtern	DUMM
34	dunkelheit	dunkellein	dunkelnauf	strengnauf	DUNKEL
35	blödheit	blödlein	blöducht	zartucht	BLÖD
36	klarheit	klarlein	klarpern	kurzpern	KLAR
37	ängstlich	ängstisch	ängstnauf	dumpfnauf	ANGST
38	pünktlich	pünktling	pünktucht	kleinucht	PUNKT
39	glücklich	glückling	glückucht	blinducht	GLÜCK
40	gesetzlich	gesetzisch	gesetzucht	ballonucht	GESETZ
41	sportlich	sportisch	sportnauf	flecknauf	SPORT
42	künstlich	künstling	künstucht	starkucht	KUNST
43	freundlich	freundisch	freundpern	soldatpern	FREUND
44	schrecklich	schreckisch	schreckucht	respektucht	SCHRECK
45	schriftlich	schriftisch	schriftucht	schmutzucht	SCHRIFT
46	fachlich	fachling	fachpern	ringpern	FACH
47	handlich	handling	handucht	fettucht	HAND
48	heimatlich	heimatisch	heimatucht	gartenucht	HEIMAT

Appendix B. Analysis of variance table for children's response times and accuracy

Response Time Analyses

	Chisq	Df	P-value	Sign.[1]
(Intercept)	153890.00	1	<.001	***
Prime Type	66.18	3	<.001	***
Affix Type	41.20	1	<.001	***
Grade	3880.50	1	<.001	***
Language	0.35	1	0.5545	
Reading Fluency	188.02	1	<.001	***
Trial Order	1.02	1	0.3131	
Prime Type:Affix Type	4.22	3	0.23834	
Prime Type:Grade	1.20	3	0.75222	
Affix Type:Grade	6.45	1	0.01109	*
Prime Type:Language	0.23	3	0.9732	
Affix Type:Language	18.58	1	<.001	***
Grade:Language	88.98	1	<.001	***
Prime Type:Reading Fluency	6.65	3	0.08402	.
Affix Type:Reading Fluency	24.35	1	<.001	***
Grade:Reading Fluency	181.96	1	<.001	***
Language:Reading Fluency	58.56	1	<.001	***
Prime Type:Affix Type:Grade	0.05	3	0.9967	
Prime Type:Affix Type:Language	9.02	3	0.02906	*
Prime Type:Grade:Language	5.87	3	0.11825	
Affix Type:Grade:Language	0.49	1	0.4842	
Prime Type:Affix Type:Reading Fluency	2.96	3	0.39769	
Prime Type:Grade:Reading Fluency	1.63	3	0.65329	
Affix Type:Grade:Reading Fluency	2.55	1	0.11035	
Prime Type:Language:Reading Fluency	9.03	3	0.02887	*
Affix Type:Language:Reading Fluency	38.11	1	<.001	***
Grade:Language:Reading Fluency	18.79	1	<.001	***
Prime Type:Affix Type:Grade:Language	6.53	3	0.0885	.
Prime Type:Affix Type:Grade:Reading Fluency	1.85	3	0.60452	
Prime Type:Affix Type:Language:Reading Fluency	2.27	3	0.51814	
Prime Type:Grade:Language:Reading Fluency	2.24	3	0.52354	
Affix Type:Grade:Language:Reading Fluency	0.08	1	0.78031	
Prime Type:Affix Type:Grade:Language:Reading Fluency	3.48	3	0.32377	

[1] Significance: '***' = <0.001; '**' = <0.01; '*' = <0.05; '.' = <0.1

Accuracy Analyses

	Chisq	Df	P-value	Sign.[1]
(Intercept)	1081.187	1	<.001	***
Prime Type	10.6795	3	0.013592	*
Affix Type	2.5655	1	0.109221	
Grade	78.0853	1	<.001	***
Language	4.1896	1	0.040672	*
Reading Fluency	122.725	1	<.001	***
Trial Order	3.9499	1	0.046874	*
Prime Type:Affix Type	0.4514	3	0.92944	
Prime Type:Grade	3.9775	3	0.263902	
Affix Type:Grade	5.1095	1	0.023795	*
Prime Type:Language	0.6555	3	0.883623	
Affix Type:Language	2.6076	1	0.106352	
Grade:Language	24.3563	1	<.001	***
Prime Type:Reading Fluency	4.7375	3	0.192058	
Affix Type:Reading Fluency	2.0565	1	0.151556	
Grade:Reading Fluency	0.0055	1	0.940965	
Language:Reading Fluency	12.41	1	<.001	***
Prime Type:Affix Type:Grade	0.0962	3	0.992288	
Prime Type:Affix Type:Language	0.4374	3	0.932412	
Prime Type:Grade:Language	2.2953	3	0.51343	
Affix Type:Grade:Language	0.0344	1	0.85277	
Prime Type:Affix Type:Reading Fluency	1.6463	3	0.648948	
Prime Type:Grade:Reading Fluency	1.2285	3	0.746185	
Affix Type:Grade:Reading Fluency	0.244	1	0.621357	
Prime Type:Language:Reading Fluency	3.0005	3	0.391541	
Affix Type:Language:Reading Fluency	0.0552	1	0.814224	
Grade:Language:Reading Fluency	0.7043	1	0.401358	
Prime Type:Affix Type:Grade:Language	0.8495	3	0.83759	
Prime Type:Affix Type:Grade:Reading Fluency	2.9756	3	0.3954	
Prime Type:Affix Type:Language:Reading Fluency	0.2996	3	0.9601	
Prime Type:Grade:Language:Reading Fluency	0.1209	3	0.989222	
Affix Type:Grade:Language:Reading Fluency	0.9062	1	0.341133	
Prime Type:Affix Type:Grade:Language:Reading Fluency	7.0671	3	0.069789	.

[1] Significance: '***' = <0.001; '**' = <0.01; '*' = <0.05; '.' = <0.1

Table 1. Demographics of child participants.

	Language	N	Mean Age (SD)	Age Range	Recruitment Area
Grade 3	French	139 (77 boys)	8.55 (0.38)	6.66-10.00	Côte d'Azur, France
	German	113 (61 boys)	8.94 (0.52)	7.91-10.42	Berlin, Germany
Grade 4	French	139 (77 boys)	9.55 (0.38)	7.67-10.92	Côte d'Azur, France
	German	113 (61 boys)	9.95 (0.52)	8.92-11.42	Berlin, Germany

Table 2. Psycholinguistic properties of French and German words (SDs in Parentheses).

Words	French	German
	Prefixed stimuli	
Number of letters of targets	6.02 (1.12)	6.02 (0.64)
Frequency/million of targets	121.47 (296.36)	99.40 (132.41)
Number of letters of affixed words	8.27 (1.22)	8.52 (0.82)
Frequency/million of affixed words	15.63 (26.32)	4.50 (5.41)
	Suffixed stimuli	
Number of letters of targets	5.29 (0.82)	5.10 (0.93)
Frequency/million of targets	132.60 (181.57)	108.53 (196.96)
Number of letters of affixed words	8.02 (1.08)	9.10 (0.93)
Frequency/million of affixed words	15.45 (19.14)	15.94 (32.58)

Table 3. Summary of RT priming effects for each participant cohort and affix type.

Affix Type	Embedded stem priming	Morpho-orthographic priming	Morpho-semantic priming
	French children		
Prefix	71ms, z =2.61, p=.009	43ms, z =3.19, p=.001	-24ms, z=1.44, p=.151
Suffix	33ms, z=2.64, p=.008	2ms, z=0.89, p=.373	27ms, z=2.07, p=.038
	German children		
Prefix	39ms, z=2.20, p=.028	10ms, z=0.50, p=.619	3ms, z=0.19, p=.849
Suffix	54ms, z=2.94, p=.003	18ms, z=1.00, p=.319	5ms, z=0.31, p=.758

Figure 1. The “word and affix” model of complex word reading (adapted from Beyersmann & Grainger, in press). Orthographic input is mapped onto the orthographic lexicon based on two mechanisms that operate in parallel: (embedded) word activation and affix activation. The principle of "morpho-orthographic full decomposition" operates in the links between the orthographic input (a string of letters) and the entities activated in the orthographic lexicon, by comparing the sum of the letters in the embedded word and the affix with the letters of the input. Representations within the orthographic lexicon are mapped onto a third layer of semantic representations. Connections between layers are bidirectional, thus allowing for bottom-up as well as top-down transfer of information between the three layers.

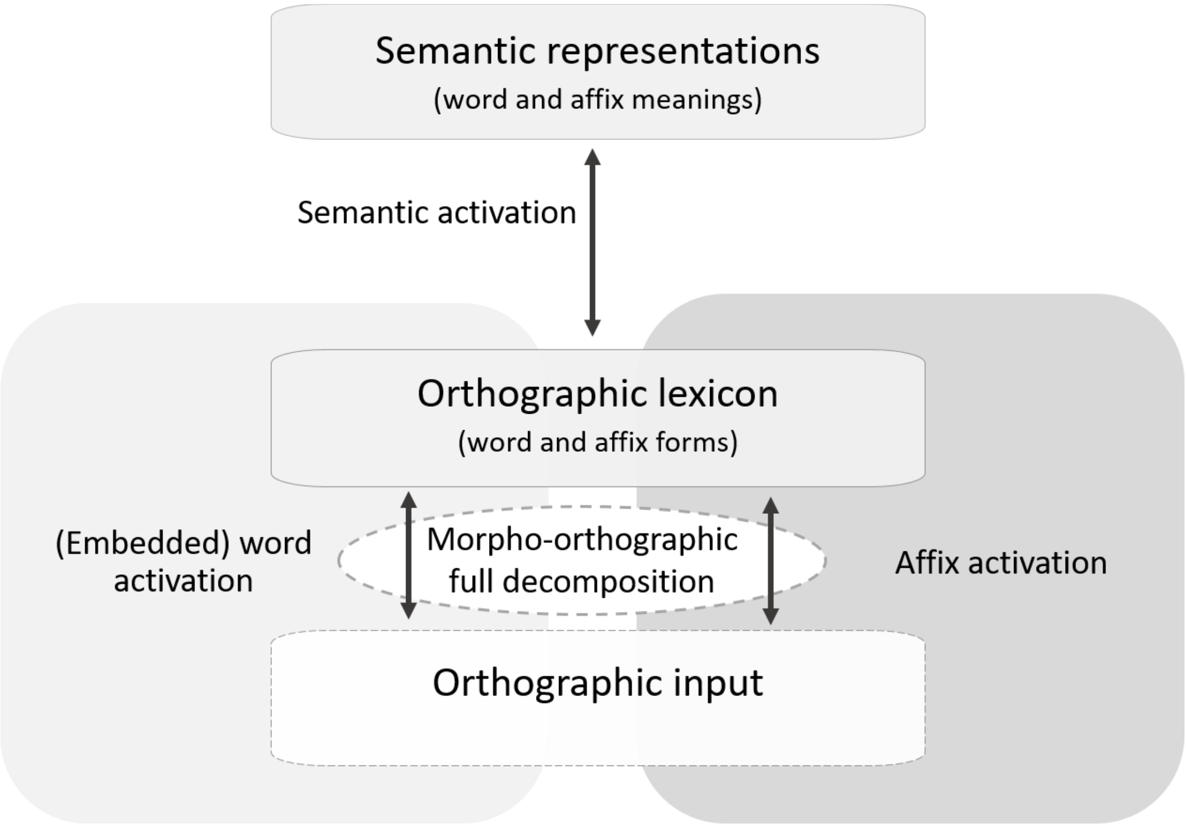

Figure 2. Lexical Decision Latencies (in Milliseconds) and Standard Errors of French and German third graders.

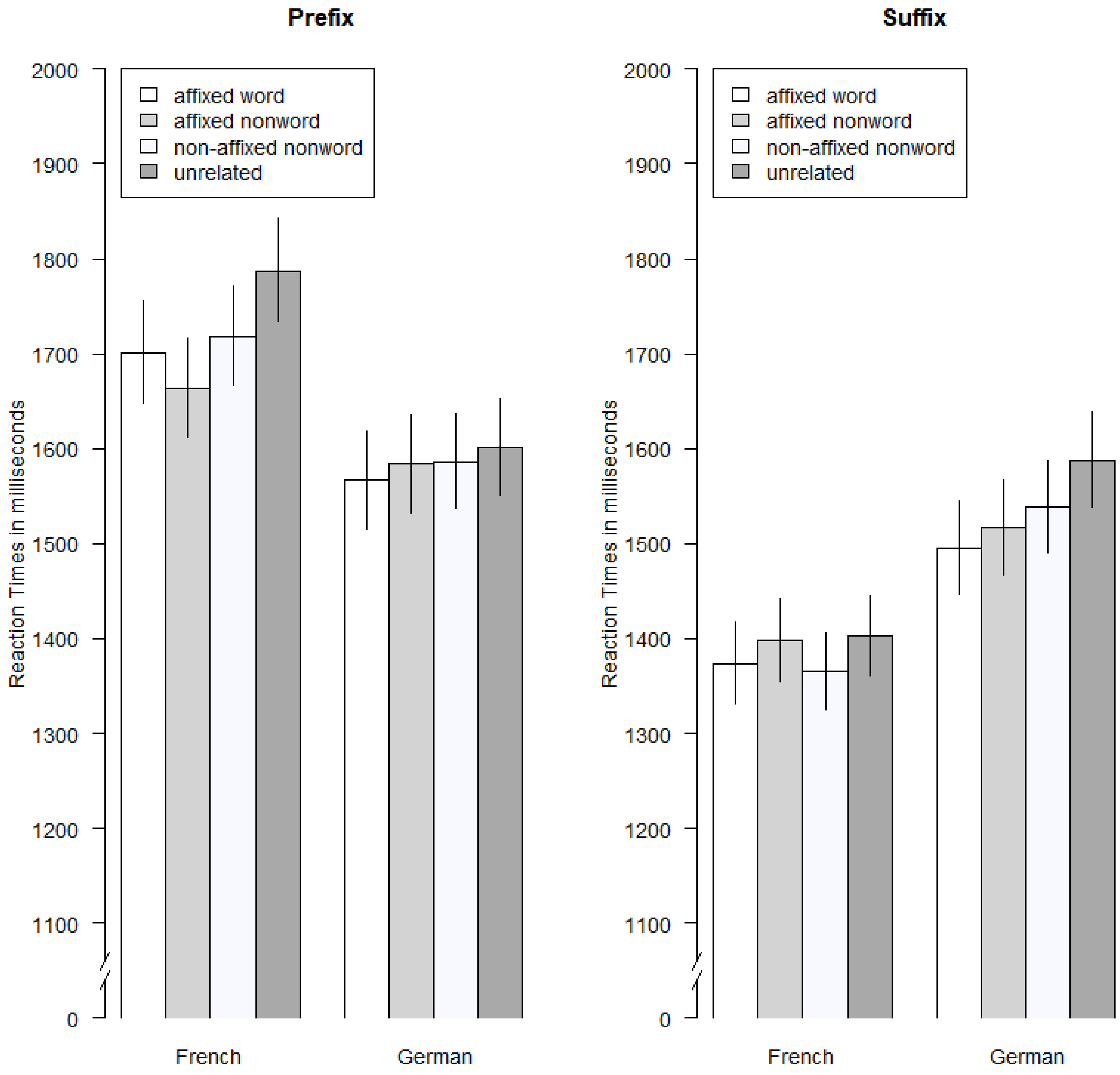

Figure 3. Lexical Decision Latencies (in Milliseconds) and Standard Errors of French and German fourth graders.

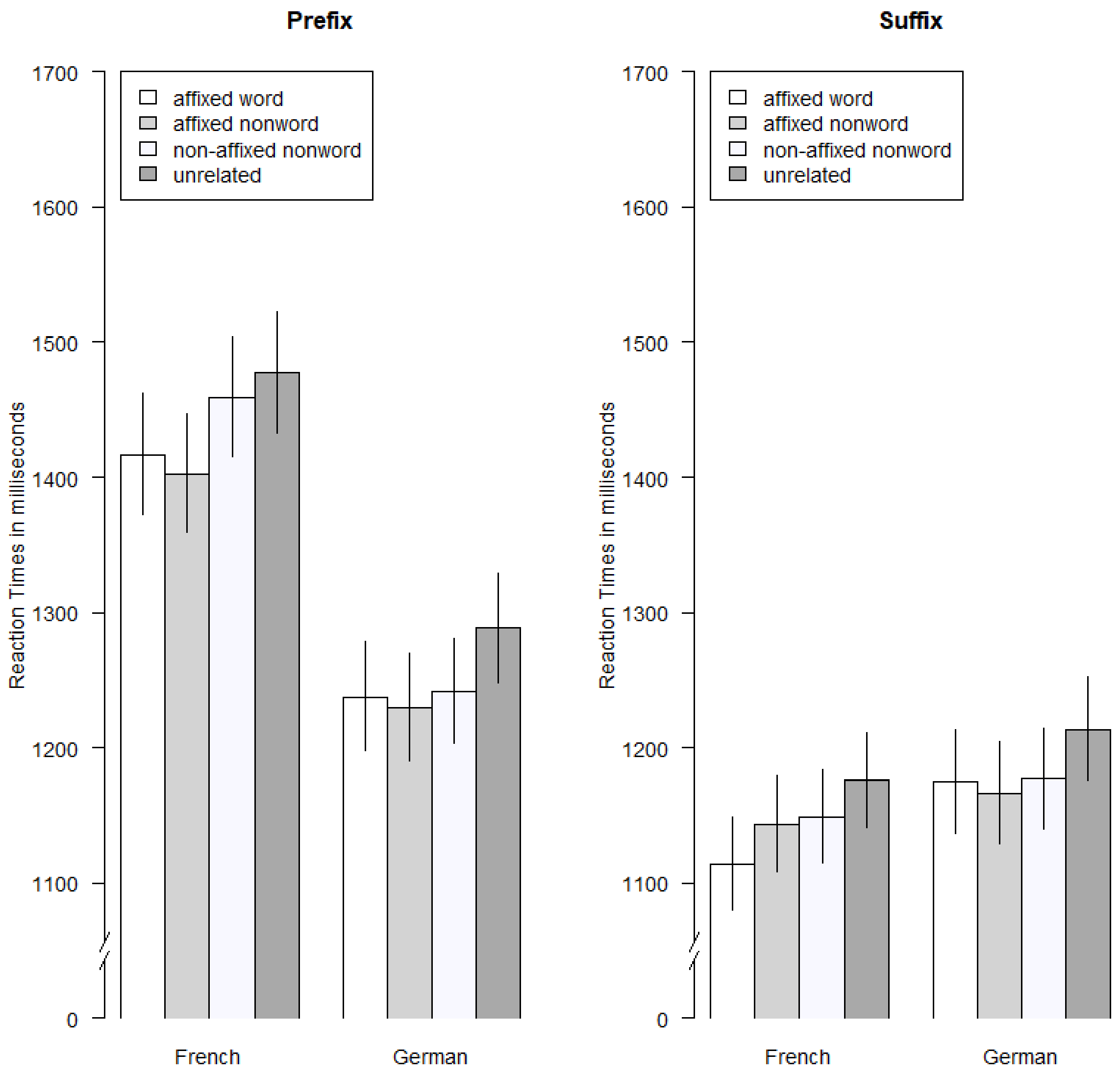

Figure 4. Priming effects in French (left panel) and German primary schoolers (right panel) as a function of individual differences in reading fluency.

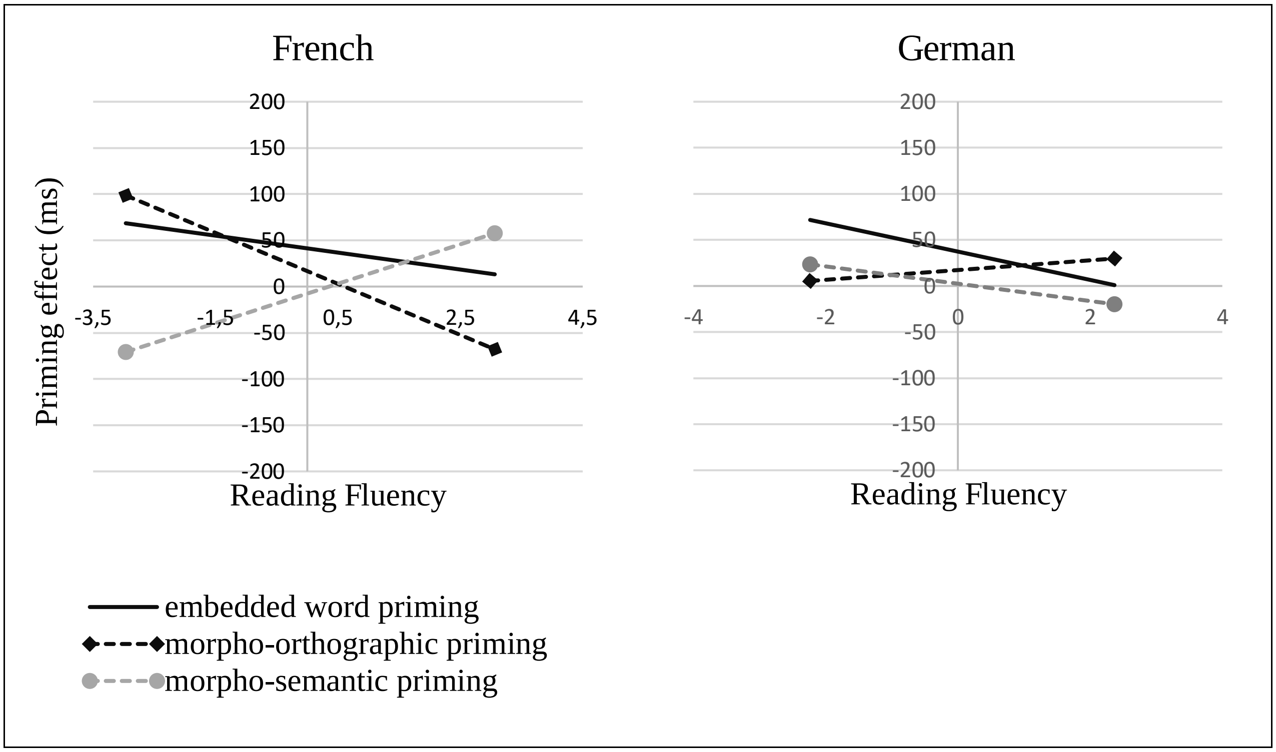

Figure 5. Error Rates and Standard Errors for French and German third graders.

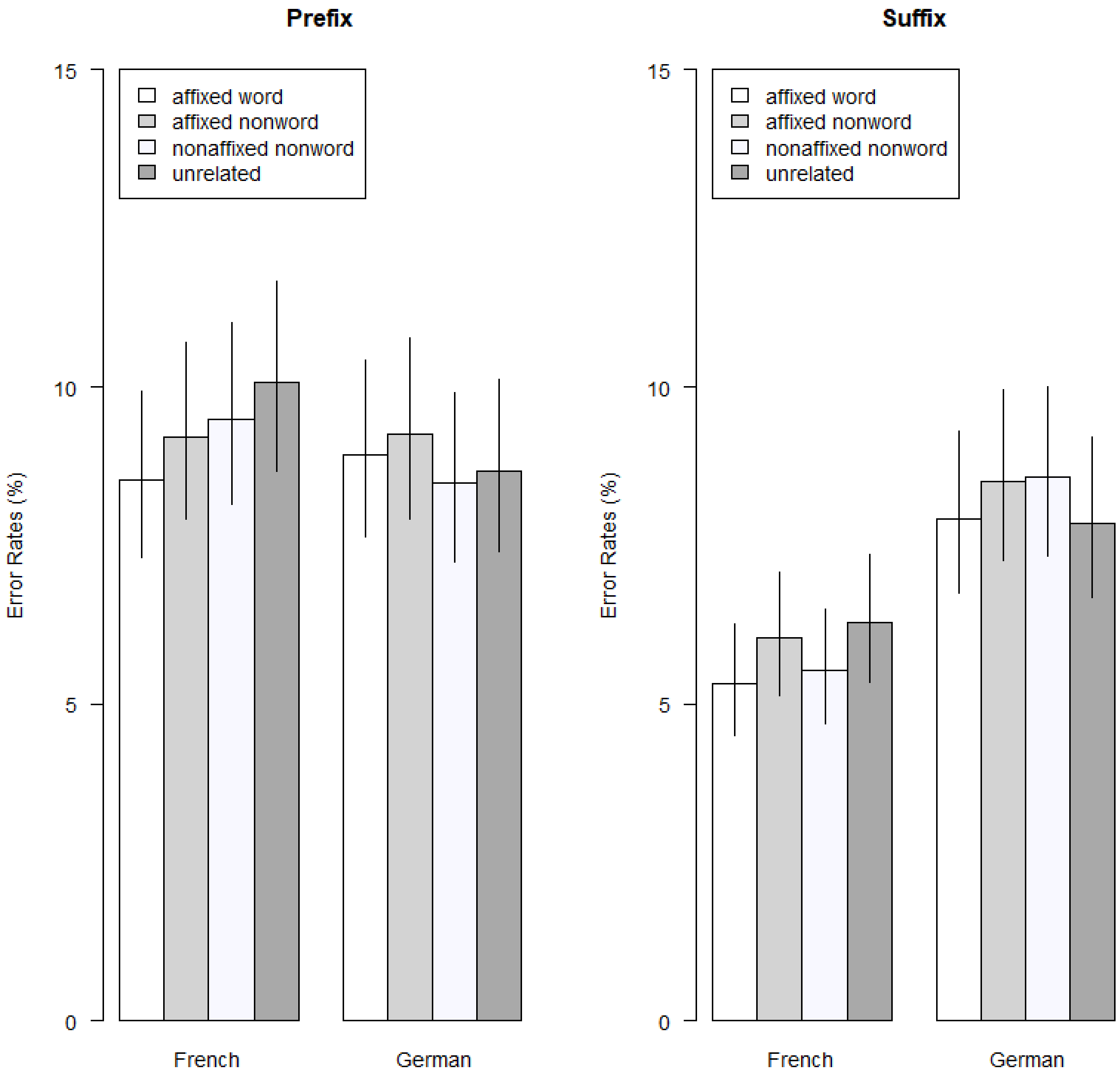

Figure 6. Error Rates and Standard Errors for French and German fourth graders.