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Morphological processing across modalities and languages

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Abstract

The present study examined cross-linguistic differences in morphological processing in the visual and auditory modality. French and German adults performed a visual and auditory lexical decision task that involved the same translation-equivalent items. The focus of the study was on nonwords, which were constructed in a way that made it possible to independently investigate the role of stems and suffixes in the visual and auditory domain. Results revealed a stem-by-modality and a suffix-by-modality interaction, indicating that morphology plays a more prominent role in the visual than in the auditory domain. Moreover, a significant language-by-stem interaction indicated more robust morphological processing in German than in French. The latter result supports the idea that morphological processing is influenced by the morphological productivity of a language.

Keywords: morphology; cross-linguistic; visual word recognition; spoken word recognition

How morphologically complex words are processed has been extensively investigated over the past few decades. However, few studies have investigated this issue across languages and modalities. The present study was designed to address two questions that have so far received little attention in the literature. The first concerns if and how mechanisms of morphological processing differ depending on whether the input stimulus is a printed letter string or a speech signal. The second asks how these mechanisms might differ across languages that vary in morphological productivity. Addressing these questions has the potential to advance theories of morphological processing by providing a broader modality-independent and language-universal perspective on visual and auditory word recognition.

Morphological processing across modalities

In many Indo-European languages with concatenative morphology, sound-to-meaning mappings of morphologically complex words are typically less consistent than spelling-to-meaning mappings (e.g., Berg & Aronoff, 2017; Berg, Buchmann, Dybiec, & Fuhrhop, 2014; Rastle, 2018; Ulicheva, Harvey, Aronoff, & Rastle, 2018). For instance, in spoken English, the past tense is usually denoted by the allomorphs /əd/, /d/, or /t/ depending on surrounding context (e.g., *busted*, *snored*, *kicked*), whereas in written English, the corresponding phonemic sequences are always spelled *ed* (e.g., Carney, 1994; Desrochers, Manolitsis, Gaudreau, & Georgiou, 2017; Rastle, 2018). Similarly, the spelling of stems is preserved (e.g., *magic*, *magical*, *magician*), although this compromises the correspondence to their spoken forms (Treiman & Bourassa, 2000). That is, some writing systems, such as English, prioritize the orthographic consistency of morphemes over that of phonemes (Bowers & Bowers, 2018), which is also referred to as the *morpheme constancy principle* (Treiman & Kessler, 2008). Morpheme constancy at the expense of grapheme-phoneme consistency is also evident in German and French (e.g., Desrochers et al., 2017; Kuo & Anderson, 2006; Peereman, Sprenger-Charolles, & Messaoud-Galusi, 2013). In German, for example, the written form of morphologically related words (e.g., *Sand-sandig*, "*sand-sandy*") is preserved even when the spoken form varies (/zant/-/zandık/), where the 'd' in 'Sand' is pronounced /t/ due to devoicing (see also Landerl & Reitsma, 2005). Similarly in French, the spellings of morphologically complex words and their embedded stems are typically consistent (e.g. *dent-dentiste, "tooth-dentist"*), whereas phonological forms tend to be more variable (e.g., the silent stem-final consonant 't' in 'dent' is pronounced when a suffix is added to the stem). Morphemic consistency enables the reader to identify morphological relationships between words, although the pronunciations of words belonging to the same morphological family may vary. Diachronic data on the evolution of suffix spellings from Old English indeed show that before the 16th Century, common spellings included -*ouse*, -*us*, or -*ows*, but were then replaced with -*ous* over time (Berg & Aronoff, 2017), thus making morphology highly visible in print (see Fuhrhop, 2011, for a similar phenomenon in German).

Of course, this does not necessarily imply that auditory and visual morphological representations in languages such as English, German, and French are unrelated. There is plenty of evidence that spoken word knowledge influences reading processes (e.g., Beyersmann et al., in press; McKague, Davis, Pratt, & Johnston, 2008; Wegener et al., 2018); and vice versa, reading influences the processing of spoken language (for a review of the evidence, see Grainger & Ziegler, 2008; see also Pollatsek & Treiman, 2015). Undoubtedly, there is an obvious transfer of written language knowledge to spoken language processing and vice versa (e.g., Frost & Ziegler, 2007). However, given the greater consistency of morphology in print, it is possible that skilled readers acquire a specialized and highly automatized morphological parsing system, which is sensitive to the presence of morphological regularities during orthographic exposure. In spoken language on the other hand, morphological processing is unlikely to reach the same level of specialization, at least in languages where the link between morphologically complex spoken forms and their embedded morphemic constituents is often inconsistent, and as such, the identification of morphological structure is less reliable. Therefore, an important question that arises is whether morphological processing is more prominent and more automatized in written compared to spoken word recognition. We sought to answer this question in the present study.

Most studies to date have examined morphological processing either in written or in spoken language using a variety of experimental paradigms (for a recent review of the literature, see Beyersmann et al., 2019). However, rarely has a study directly compared morphological processing in the visual and auditory modality. Findings from the visual word recognition domain suggest that adults are experts at rapidly and automatically identifying morphological structures in print, independently of semantics (e.g., Amenta & Crepaldi, 2012; Beyersmann, Ziegler, et al., 2016; Longtin, Segui, & Hallé, 2003; Rastle & Davis, 2008; Rastle, Davis, & New, 2004). In contrast, a review of the spoken word recognition literature (Beyersmann et al., 2019) indicates that morphological processing may be more reliant on semantics in this modality (Marslen-Wilson, Tyler, Waksler, & Older, 1994; Meunier & Longtin, 2007; Wurm, 1997, 2000; Wurm & Ross, 2001). On the basis of the available empirical evidence then, form-based morphological processing is likely to be more prominent in visual than in auditory word identification.

Two studies so far have directly tested differences in morphological processing between the spoken and written modality using a visual and auditory lexical decision task (Gafni, Yablonski, & Ben-Shachar, 2019; Leinonen et al., 2009). Gafni et al. (2019) found that in both modalities, participants responded slower to Hebrew pseudowords that contained real morphemes than to pseudowords that contained invented morphemes, a finding that has been typically referred to as the “morpheme interference effect” (MIE) and has been replicated across several languages, including English, Italian, French, Swedish, and Hebrew (e.g., Caramazza, Laudanna, & Romani, 1988; Casalis, Quemart, & Duncan, 2015; Crepaldi, Rastle, & Davis, 2010; Gafni et al., 2019; Jarvella & Wennstedt, 1993; Taft & Forster, 1975; Yablonski & Ben-Shachar, 2016). Gafni et al. observed that the effect was more robust in the visual compared to the auditory modality. Leinonen et al. (2009) showed, again in both modalities, that participants responded more slowly to inflected Finnish words compared to monomorphemic words, but there was no difference between affixed and non-affixed nonwords. Leinonen et al. thus failed to observe the standard MIE in their behavioral data. However, the authors additionally recorded event-related potentials (ERPs). The ERPs confirmed that inflected words elicited a more negative N400 compared to monomorphemic words. The single word N400 component is generally thought to reflect word form processing difficulty (e.g., Perre, Midgley, & Ziegler, 2009; Winsler, Midgley, Grainger, & Holcomb, 2018), with N400 amplitude increasing with an increased difficulty in identifying words and associating them with meaning (e.g., Grainger & Holcomb, 2009). The greater N400 for inflected words compared to monomorphemic ones was obtained in both modalities, which the authors interpreted as processing costs associated with access and possible integration of the stem and the suffix. Leinonen and colleagues also reported a significant N400 effect for inflected compared to non-inflected nonwords, which was significant in the visual but not in the auditory modality. Thus, the results from these two prior studies provide some initial evidence that morphological structure may have a greater impact on visual than on auditory language processing.

Morphological processing across languages

Given that Finnish and Hebrew are morphologically productive languages, it is possible that the observed effects were due to the prominent role of morphology in Finnish and Hebrew. This relates to the second question we addressed in this study, which is whether morphological processing in the visual and auditory modality may be modulated by the morphological productivity of a language. Morphological productivity refers to how specific morphological word-formation patterns may be used in the production of new forms (Bauer, 2001). Morphemic units (including both affixes and stem morphemes) display large variability in morphological productivity (Hay & Baayen, 2002). The more often a morpheme occurs in morphologically complex forms in the lexicon, the more productive it is thought to be. Critically, languages differ in this respect. For example, according to two widely-used methods in the literature, namely, Juola (1998, 2008) and Type-token ratio (TTR; Kettunen, 2014), French is morphologically less complex than German. It has been suggested that the abundant presence of compound words in German (e.g., Creutz & Lagus, 2005; Creutz, Lagus, Lindén, & Virpioja, 2005; Fleischer & Barz, 1995; Meyer, 1993) may be the reason why German appears to be more morphologically complex (Sadeniemi, Kettunen, Lindh-Knuutila, & Honkela, 2008). German compounds are mostly right-headed and concatenated (*Großvater* [engl. grandfather]), whereas French compounds are typically left-headed and non-concatenated (*chef de police* [engl. chief of police]) or hyphenated (*grand-père* [engl. grandfather]) (Nicoladis & Krott, 2007). The latter type is less frequent than the former and not very productive (Nicoladis, 2001). German also permits the compounding of multiple meaning conveying units (e.g. *Datenschutzexpertentagungshotel* [engl. Meeting hotel for data protection experts]), which are generally written without intervening spaces (e.g., Inhoff, Radach, & Heller, 2000).

Given these key linguistic differences between French and German, we hypothesized that morphological processing should be more robust in German than in French. Specifically, Germans should be more expert at rapidly extracting embedded stem morphemes from fully concatenated complex forms. As opposed to affixes, stems are free-standing morphemes that can be mapped onto existing representations in the mental lexicon and therefore do not require a specialized morphological chunking mechanism (Grainger & Beyersmann, 2017). Grainger and Beyersmann (2017) therefore argued that the mechanism by which stems are recognized is distinct from the mechanism by which affixes are being identified. Due to their high exposure to compound words, German speakers might develop a higher level of proficiency at mapping embedded stems onto existing lexical representations than speakers of French, which would then be reflected in more robust embedded-stem effects in German than in French.

Present study

To test differences in morphological processing between the visual and auditory modality in French and German, we used an experimental paradigm that allowed us to tightly control for both item- and language-specific variables. We conducted an auditory and a visual lexical decision task using the same translation-equivalent items in both tasks. We focused on the processing of morphologically complex nonwords by manipulating orthogonally the stem and the suffix. In particular, four conditions were created: Stem+Suffix, Stem+Non-Suffix, Non-Stem+Suffix, and Non-Stem+Non-Suffix. The primary advantage of this 2x2 design was that it allowed us to tease apart the separate roles of the stem and the suffix, as well as their interactions. The selection of nonwords provided greater control over psycholinguistic variables that are known to influence language processing (e.g., word frequency).

Previous studies

It is worth noting that a number of studies in this research domain have included complex nonwords in their investigations, but these have been typically restricted to the comparison between Non-Stem+Affix vs. Non-Stem+Non-Affix (Lavric, Elchlepp, & Rastle, 2012; Zweig & Pylkkänen, 2009), Stem+Affix vs. Non-Stem+Affix (Taft & Forster, 1975), Non-Stem+Suffix vs. Non-Stem+Non-Suffix vs. Stem+Non-Suffix (Vannest, Newport, Newman, & Bavelier, 2011), or Stem+Suffix vs. Stem+Non-Suffix (Beyersmann et al., 2019; Dawson, Rastle, & Ricketts, 2018). What these prior studies concurrently show is that the presence of morphemes in nonwords makes the process of rejecting a nonword in lexical decision harder, thus replicating the typical MIE pattern (e.g., Caramazza et al., 1988; Casalis et al., 2015; Crepaldi, Rastle, & Davis, 2010; Gafni et al., 2019; Jarvella & Wennstedt, 1993; Taft & Forster, 1975; Yablonski & Ben-Shachar, 2016). However, what these studies were less able to address due to the lack of a full factorial design are the combined effects of stem and affix.

Hypotheses

We hypothesized that a suffix effect would be evidenced by slower reaction times (RTs) and higher error rates in the Suffix compared to the Non-Suffix conditions, whereas a stem effect would be evidenced by slower RTs and higher error rates in the Stem compared to the Non-Stem conditions. This is because the presence of a suffix and/or a stem in nonwords should make their rejection harder during lexical decision by providing more evidence in favor of a "word" response. The combined stem and suffix effects should further result in a significant Stem-by-Suffix interaction, because the stem effect would be larger for suffixed than for non-suffixed nonwords. We also expected more robust stem and suffix effects in the visual compared to the auditory modality (i.e., evidenced by significant Stem-by-Modality and Suffix-by-Modality interactions), because morphological structure is more consistently represented in print than aurally. Moreover, on the assumption that the morphological productivity of a language influences the degree of morphological processing both visually and aurally, we hypothesized that morphological processing, and in particular embedded stem recognition, should be more robust in German than in French (i.e., evidenced by a robust Language-by-Stem interaction). On the assumption that morphological productivity in German is attributed to its rich compounding rather than its derivational system (Sadeniemi et al., 2008), it was less clear whether a Language-by-Suffix interaction would also emerge. If anything, this should be weaker or smaller in size than the Language-by-Stem interaction.

Finally, as a by-product of our key hypotheses listed above, it was further predicted that the additive weight of the larger morphology effects in the visual modality, and the larger morphology effects in the German language, would result in an overall larger modality effect in German (evidenced by a significant Language-by-Modality interaction), as well as larger morphology effects in the visual modality in German (evidenced by a significant Language-by-Modality-by-Stem interaction, and possibly a significant Language-by-Modality-by-Suffix interaction).

Experiment

Method

Participants. A total of 96 adults, 48 French (4 males, 5 left-handed, Mean Age = 19.0, SD = 1.7) and 48 German (11 males, 5 left-handed, Mean Age = 24.7, SD = 3.8) participated in the study for monetary compensation. Participants were native speakers of their respective language, had normal or corrected-to-normal vision, and reported no hearing, reading, or language difficulties. Five French participants were bilingual (French-Italian, French-Portuguese, or French-English) and one was trilingual (French-Malagasy-English). Two German participants were bilingual (German-English, German-Bulgarian). The study was approved by the ethics committees of Aix-Marseille Université and the Max Planck Institute for Human Development. Prior to participating in the study, participants provided written, informed consent. Each participant completed both the visual and the auditory lexical decision task, while the order of the tasks was counterbalanced across participants.

Materials. Sixty morphologically simple words corresponding to translation-equivalent nouns (e.g., *nuit, Nacht* [engl. night]), which often happened to be cognates, were selected from each language. Also, five noun-forming, translation-equivalent suffixes in the two languages were chosen (see Table 1 for details concerning the selected suffixes). The French and German suffixes were matched as closely as possible on number of letters (M = 3.6, SD = 0.5 vs. M = 3.4, SD = 0.6; $t(4)$ = 0.54, p =.621), number of phonemes (M = 2.0, SD = 0.6 vs. M = 2.8, SD = 0.6; $t(4)$ = 1.37, p =.242), and raw suffix type frequency, i.e., the number of words in the language that comprise the suffix (M = 1921, SD = 1214 vs. M = 1669, SD = 1548; $t(4)$ = 0.94, p = .400, for French and German, respectively).[1]

Table 1. Translation equivalent French and German suffixes and their meanings.

German	French	English*	Examples (German; French)	Suffix meaning
ung	ion	ion	Trennung; separation (Engl. separation)	(result of) an action or process
bar	able	able	ersetzbar; remplaçable (Engl. replaceable)	able to be done; suitable; subject to
keit	ment	ment	Dankbarkeit, remerciement (Engl. acknowledgement)	action or result of what is denoted by the stem

[1] Suffix frequencies were extracted from CELEX (Baayen, Piepenbrock, & van Rijn, 1993) for German and Lexique (New, Pallier, Brysbaert, & Ferrand, 2004) for French. We note however that the suffix frequency measures for the two languages are not directly comparable, because the size of the corresponding corpora and the morphological segmentation methods that were used in each case differed.

er	eur	er	Arbeiter, travailleur (Engl. worker)	forms agent nouns from the stem
haft	eux	ful	zweifelhaft; douteux (Engl. doubtful)	possessing the quality expressed by the stem

*English translations are provided for reporting purposes only.

Stems were either combined with suffixes, forming nonwords in the Stem+Suffix condition (e.g., *nuit**eur**, Nacht**er*** [engl. nighter]), or a letter sequence that did not correspond to a suffix, forming nonwords in the Stem+Non-Suffix condition (e.g., *nuit**erge**, Nacht**atz*** [engl. nightel]). After a letter was replaced in these stems, the resulting non-stems (i.e., nonwords) were combined with the same suffixes, forming nonwords in the Non-Stem+Suffix condition (e.g., *nait**eur**, Necht**er*** [engl. naghter]), or the same letter sequences, forming nonwords in the Non-Stem+Non-Suffix condition (e.g., *nait**erge**, Necht**atz*** [engl. naghtel]). In addition, sixty words that also corresponded to translation-equivalent nouns in the two languages were selected and included in the study for the purpose of the lexical decision task. Half of these words, which often happened to be cognates too, were suffixed, hence morphologically complex (e.g., *boulanger, Bäcker* [engl. baker]), while the remaining half were non-affixed (e.g., *diamant, Diamant* [engl. diamond]), hence morphologically simple.[2]

Word frequency and Orthographic Levenshtein distance (OLD20: Yarkoni, Balota, & Yap, 2008), were extracted from Lexique (New et al., 2004) for French, and SUBTLEX-DE (Brysbaert et al., 2011) for German.[3] All items are shown in the Appendix and their

[2] Due to an oversight, three German non-suffixed words (*Bescheid, Existenz, Frisur*) were originally incorrectly chosen as suffixed. However, for the calculation of the psycholinguistic properties of the items and the analyses, these items were classified as non-suffixed.

[3] It is worth noting that just like suffix frequencies, stem frequencies in the two languages cannot be directly compared, because the size of the corresponding corpora are substantially different.

psycholinguistic properties are displayed in Tables 2 and 3. It is worth noting that our strategy to use translation-equivalent stems and suffixes in French and German did not allow us to fully match the corresponding nonwords on OLD20, number of letters, and number of phonemes (see statistics in Table 2). Hence, we controlled for these differences by including these variables as covariates in the statistical models.

Both the French and the German auditory targets were produced with the OS X Speech Synthesizer. The naturalness of the synthesized files was checked by two independent native speakers in each language. Auditory files were edited to ensure that any silence at the beginning and end of each item was removed.

Table 2. Psycholinguistic Properties of French and German Nonwords (SDs in Parentheses).

Nonwords	Stem+Suffix	Stem+Non-Suffix	Non-stem+Suffix	Non-stem+Non-Suffix
		French		
OLD20	2.5 (0.6)	2.9 (0.5)	2.7 (0.6)	3.2 (0.6)
N letters	8.1 (1.3)	8.2 (1.1)	8.1 (1.3)	8.1 (1.2)
N phonemes	5.7 (1.3)	6.2 (1.1)	5.9 (1.3)	6.3 (1.2)
		German		
OLD20	2.8 (0.6)	2.7 (0.5)	3.0 (0.7)	2.9 (0.5)
N letters	7.7 (1.2)	7.3 (1.2)	7.7 (1.2)	7.3 (1.2)
N phonemes	6.8 (1.1)	6.8 (1.1)	6.9 (1.1)	6.9 (1.1)
		French vs. German		
OLD20	t(59)=-3.555, p = .001	t(59)=2.271, p = .027	t(59)=-3.089, p = .003	t(59)=3.520, p = .001

N letters	t(59)=2.560, p = .013	t(59)=4.597, p < .001	t(59)=2.560, p = .013	t(59)=4.678, p < .001
N phonemes	t(59)=-5.169, p < .001	t(59)=-3.500, p = .001	t(59)=-4.738, p < .001	t(59)=-2.929, p = .005

Table 3. Psycholinguistic Properties of French and German Suffixed Words, Non-Suffixed Words and Stems of Nonwords (SDs in Parentheses).

Words	Suffixed Words	Non-Suffixed Words	Stems of Nonwords
		French	
OLD20	2.3 (0.5)	2.0 (0.5)	1.5 (0.4)
N letters	8.1 (1.2)	6.7 (0.8)	4.6 (1.0)
N phonemes	6.4 (1.4)	5.0 (0.9)	3.2 (1.0)
Frequency	4.0 (0.6)	3.7 (0.6)	4.4 (0.9)
		German	
OLD20	2.3 (0.5)	2.3 (0.4)	1.4 (0.4)
N letters	7.7 (1.2)	6.7 (0.8)	4.3 (1.0)
N phonemes	6.3 (1.1)	6.2 (1.3)	4.0 (0.9)
Frequency	4.1 (0.5)	3.8 (0.6)	4.7 (0.6)

Procedure. Three hundred items (60 words and 240 nonwords) in each language were used in the study. The nonword items belonged to four conditions: Stem+Suffix, Stem+Non-Suffix, Non-Stem+Suffix, Non-Stem+Non-Suffix. The word items belonged to two conditions: Suffixed and Non-Suffixed. Four lists were created with each target word appearing once in every list and each target nonword appearing once across the four lists. Thus, each list comprised

120 items, 60 nonwords (15 in each condition) and 60 words (30 in each condition). Hence, all conditions were represented in each list. An equal number of participants were assigned to each list. The word and nonword items were presented intermixed. The order of trial presentation within each list was randomized across participants. Six practice items consisting of both words and nonwords were presented to the participants prior to the experimental trials.

Participants were tested individually, seated approximately 60 cm in front of a laptop or a PC monitor in a quiet room. Stimulus presentation and RTs were controlled by DMDX software (Forster & Forster, 2003). In the visual lexical decision task, participants were told that words and nonwords would appear on the screen one at a time. Participants were then instructed to press “K” if the letter string was a word and “D” if the letter string was a nonword. Items were presented in lowercase letters. However, the first letter of the German items was uppercase, because the first letter of noun forms in German is always written in uppercase. For consistency, all German items were presented in the same format. Stimuli appeared in white on a black background (20-point Arial font) and remained on the screen for 3000 ms or until participants responded, whichever happened first. In the auditory lexical decision task, participants wore headphones and were told that they would hear a word or a nonword one at a time. Participants had to press the same buttons as for the visual lexical decision task to indicate whether the item they heard was a word or a nonword. A black cross appeared on a white background while the item was presented aurally, and remained on the screen for 3000 ms or until participants responded, whichever happened first. RTs were recorded from stimulus onset. In both tasks, participants were asked to respond as quickly and as accurately as possible.

Analyses

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 3.6.1, 2019-07-05, "Action of the Toes", RCoreTeam, 2018). 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 3.0-4; Fox & Weisberg, 2011). 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.

Results

The data from both languages and tasks were analyzed together. Given that nonwords were the focus of interest in the present study, we only report the nonword analyses. First we report the RT analyses and then the accuracy analyses. The results from the mixed-effects analyses are provided in Table 4 and the mean model RTs and error rates are displayed in Figures 1 and 2.

Table 4. Summary of Linear Mixed-Effects Analyses for Nonword RTs and Accuracy.

Variables	RTs		Accuracy	
	χ^2	*p*	χ^2	*p*
Fixed effects (*df*)				
Intercept (1)	287390.000	<.001	950.155	<.001
Language (1)	47.243	<.001	1.688	=.194
Stem (1)	116.610	<.001	79.790	<.001
Suffix (1)	21.028	<.001	59.600	<.001
Modality (1)	6099.800	<.001	0.635	=.426
Stem:Suffix (1)	24.379	<.001	1.130	=.288
Stem:Modality (1)	32.021	<.001	8.279	=.004
Suffix:Modality (1)	111.290	<.001	0.811	=.368
Language:Stem (1)	6.317	=.012	1.389	=.239
Language:Suffix (1)	3.592	=.058	1.851	=.174
Language:Modality (1)	112.770	<.001	0.041	=.840
Language:Stem:Suffix (1)	2.243	=.134	0.168	=.682
Language:Stem:Modality (1)	11.006	=.001	4.714	=.030
Language:Suffix:Modality (1)	0.178	=.673	0.288	=.591
Stem:Suffix:Modality (1)	12.184	<.001	2.676	=.102
Language:Stem:Suffix:Modality (1)	0.001	=.977	3.947	=.047
Order	155.580	<.001		
OLD20	26.390	<.001	40.827	<.001
Letter Length	56.361	<.001	22.706	<.001
Phoneme Length	36.216	<.001	2.141	=.143

Reaction Times

Incorrect responses to nonwords (7.1% of the data) were first removed. Latencies below 200 or above 2000 ms (1.3% of the data) were considered as extreme values and were also removed. Outliers were removed following the procedure outlined by Baayen and Milin (2010). A base model, which included only participants and items as random intercepts, was fitted to the data and data points with residuals exceeding 2.5 *SD*s were removed (0.7% of the data). The LME model included the effect-coded fixed effects of Language (French vs. German), Stem (Stem vs. Non-Stem), Suffix (Suffix vs. Non-Suffix), and Modality (Auditory vs. Visual), as well as their interaction. Trial Order, OLD20, Letter Length, and Phoneme Length (all standardized) were included in the model as covariates. Trial order was included to control for task effects such as fatigue or habituation. OLD20, Letter Length, and Phoneme Length were included to control for the observed differences between the German and French nonword stimuli (see Table 2). Random intercepts and random slopes for the effects of Stem and Suffix, and their interaction, were used for both participants and items. Cohen's d was calculated to establish effect sizes.

Stem and suffix effects

The main effect of Stem was significant ($\chi^2(1) = 116.610$, $p < .001$). Nonwords with stems (M = 922 ms, SE = 12) were responded to significantly slower (Δ = 62 ms, z = 10.800, $p < .001$, d = 0.29) than nonwords without stems (M = 861 ms, SE = 11). Also, the main effect of Suffix was significant ($\chi^2(1) = 21.028$, $p < .001$). Nonwords with suffixes (M = 904 ms, SE = 12) were responded to significantly slower (Δ = 26 ms, z = 4.586, $p < .001$, d = 0.12) than nonwords without suffixes (M = 878 ms, SE = 11). Moreover, the Stem by Suffix interaction was significant ($\chi^2(1) = 24.379$, $p < .001$). The stem effect for suffixed nonwords (Δ = 89 ms, z = 10.890, $p < .001$, d = 0.41) was substantially larger than the stem effect for non-suffixed nonwords (*Δ* = 35 ms, *z* = 4.781, *p* <.001, *d* = 0.17). The effect sizes for the stem effect and the stem effect for suffixed nonwords were medium, whereas the suffix effect and the stem effect for non-suffixed nonwords were small.

Modality effects

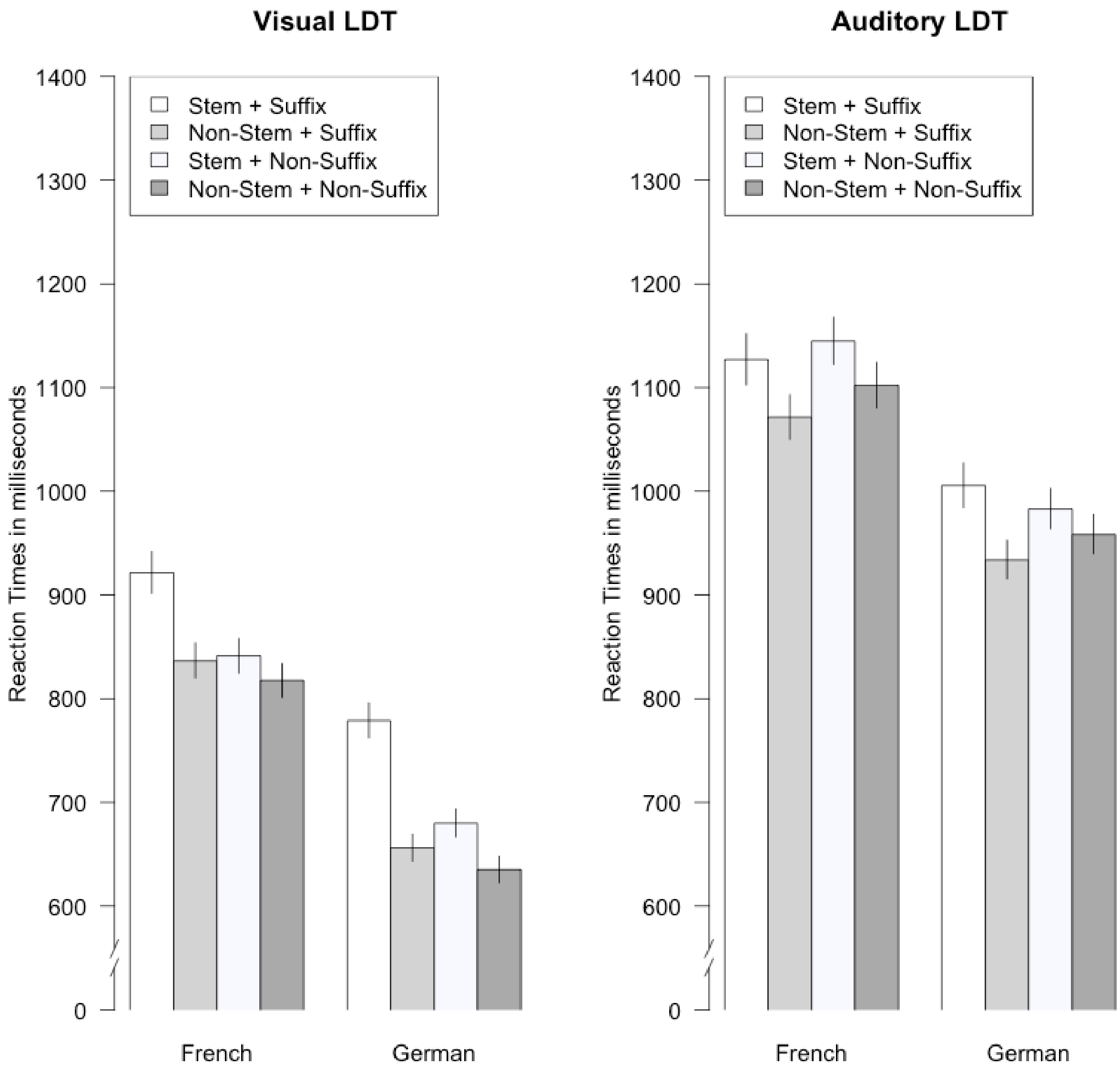
The main effect of Modality was significant (χ^2(1) = 6099.800, *p* <.001). Nonwords in the auditory modality (*M* = 1038 ms, *SE* = 13) were responded to significantly slower (*Δ* = 273 ms, *z* = 78.100, *p* <.001, *d* = 1.29) than nonwords in the visual modality (*M* = 765 ms, *SE* = 10). Furthermore, the interaction between Stem and Modality was significant (χ^2(1) = 32.021, *p* <.001). The stem effect in visual modality (*Δ* = 70 ms, *z* = 12.150, *p* <.001, *d* = 0.38) was larger than the stem effect in auditory modality (*Δ* = 49 ms, *z* = 6.273, *p* <.001, *d* = 0.20). Also, the interaction between Suffix and Modality was significant (χ^2(1) = 111.290, *p* <.001). The suffix effect was significant in visual modality (*Δ* = 54 ms, *z* = 9.390, *p* <.001, *d* = 0.30), but not in auditory modality (*Δ* = 12 ms, *z* = 1.575, p = .115, *d* = 0.05). Accordingly, the triple Stem by Suffix by Modality interaction was significant (χ^2(1) = 12.184, *p* <.001). This was because the stem effect was much larger for suffixed nonwords than for non-suffixed nonwords in the visual modality (*z* = 6.035, *p* <.001, *d* = 0.36), compared to the auditory modality (*z* = 2.188, *p* = 0.029, *d* = 0.13). The effect size for the modality effect was large. The stem effect, the suffix effect, and the stem effect for nonwords containing suffixes compared to nonwords containing non-suffixes were medium in the visual modality, but small in the auditory modality.

Language effects

The main effect of Language was significant (χ^2(1) = 47.243, *p* <.001). French participants (*M* = 974 ms, *SE* = 18) were significantly slower (*Δ* = 158 ms, *z* = 6.873, *p* <.001, *d* = 0.75) than German participants (*M* = 815 ms, *SE* = 15). Critically for the hypotheses tested in the present study, the Language by Stem interaction was significant ($\chi^2(1) = 6.317$, $p = .012$). The stem effect in German (Δ = 69 ms, $z = 9.580$, $p < .001$, $d = 0.36$) was much larger than the stem effect in French (Δ = 52 ms, $z = 5.925$, $p < .001$, $d = 0.22$). The Language by Suffix interaction only approached significance ($\chi^2(1) = 3.592$, $p = .058$). In addition, the interaction between Language and Modality was significant ($\chi^2(1) = 112.770$, $p < .001$). Differences between the visual and aural tasks in German (Δ = 284 ms, $z = 63.580$, $p < .001$, $d = 1.46$) were much larger than differences between the two types of tasks in French (Δ = 258 ms, $z = 47.100$, $p < .001$, d = 1.11). As per our predictions, the interaction between Language, Stem, and Modality were significant ($\chi^2(1) = 11.006$, $p = .001$). Post-hoc contrasts showed that the stem effect was not modulated by type of task in French ($z = 1.635$, $p = 0.102$, $d = 0.08$), but it was significantly bigger in the visual than in the auditory modality in German ($z = 6.428$, $p < .001$, $d = 0.30$). The effect size for the language effect was large. The sizes of the stem effect and the stem effect in the visual compared to the auditory modality, were medium in German, but small in French. The modality effect was large in both German and French.

Taken together, our results show that morphology plays an important role both visually and aurally. However, morphological influences were found to be more robust in the visual than in the auditory domain. In addition, the impact of morphological structure was greater in German than in French. Also, compared to French, the observed morphological effects in German were more prominent in the visual than in the auditory modality.

Figure 1. Lexical Decision Latencies (in Milliseconds) and Standard Errors for Nonwords in Visual and Auditory LDT.



Accuracy

The error analyses were conducted in the same way as for RTs. The GLME model included the same fixed effects and interactions as the LME model. OLD20, Letter Length, and

Phoneme Length (all standardized) were included in the model as covariates. Odds Ratios (ORs) were calculated to establish effect sizes (Chen , Cohen, & Chen, 2010).

Stem and suffix effects

The main effect of Stem was significant ($\chi^2(1) = 79.790$, $p < .001$). Nonwords with stems ($M = 5.0$, $SE = 0.5$) yielded more errors ($\Delta = 3.3$, $z = 7.608$, $p < .001$, OR = 2.081) than nonwords without stems ($M = 1.7$, $SE = 0.2$). Also, the main effect of Suffix was significant ($\chi^2(1) = 59.600$, $p < .001$). Nonwords with suffixes ($M = 5.4$, $SE = 0.6$) yielded more errors ($\Delta = 3.8$, $z = 7.844$, $p < .001$, OR = 1.980) than nonwords without suffixes ($M = 1.6$, $SE = 0.2$). The sizes of the stem and suffix effects were medium (see Chen et al., 2010).

Modality effects

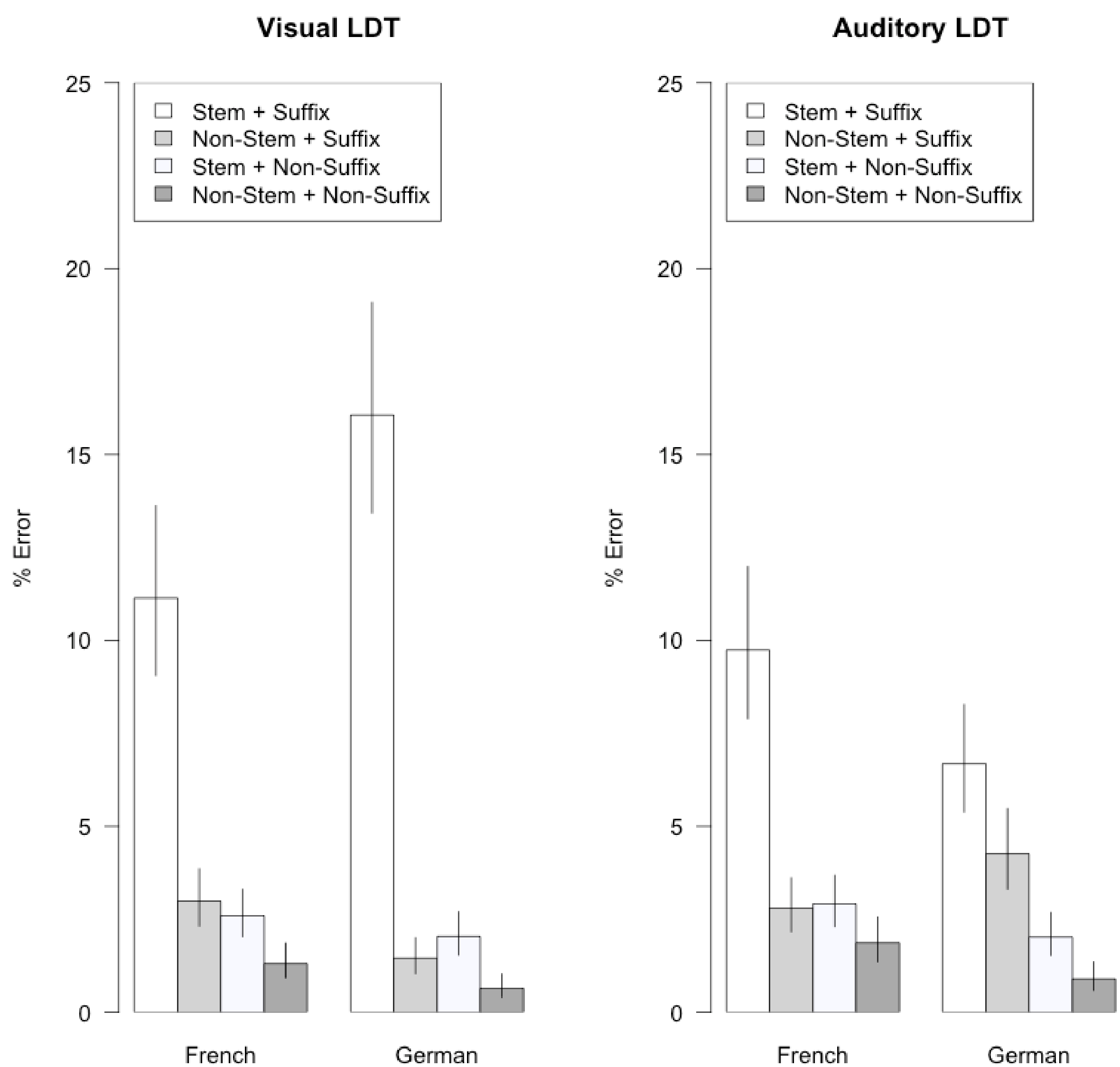
The interaction between Stem and Modality was significant ($\chi^2(1) = 8.279$, $p = .004$). Nonwords with stems yielded more errors in the visual modality ($\Delta = 4.3$, $z = 7.505$, $p < .001$, OR = 4.304) than in the auditory modality ($\Delta = 2.4$, $z = 4.349$, $p < .001$, OR = 2.166). The stem effect had a medium effect size in both modalities.

Language effects

The interaction between Language, Stem, and Modality was significant ($\chi^2(1) = 4.714$, $p = .030$). Post-hoc contrasts showed that the stem effect was not modulated by type of task in French ($z = 0.598$, $p = .550$, OR = 1.173), but it was significantly bigger in visual than in auditory modality in German ($z = 3.247$, $p = .001$, OR = 3.367). Similarly to the analyses of response latencies, the size of the stem effect in the visual compared to the auditory modality was medium in German, but small in French. In addition, the interaction between Language, Stem, Suffix, and Modality was significant ($\chi^2(1) = 3.947$, $p = .047$). This was because the stem effect for nonwords with and without suffixes was similar across modalities in French ($z = 0.302$, *p* = .763, OR = 1.174), but it was much bigger in the visual than in the auditory modality in German (z = 2.353, p = .019, OR = 5.808). The corresponding effect sizes were very small in French and large in German.

Taken together, the results from the analyses on nonword accuracy showed that morphological effects in German are more prominent in the visual than in the auditory modality.

Figure 2. Accuracy (% Error) and Standard Errors for Nonwords in Visual and Auditory LDT.



Discussion

The present study is the first to investigate morphological processing in different modalities in a cross-linguistic fashion. We focused our investigations on four types of morphologically complex nonwords to tease apart the separate effects of morphemic stems and suffixes. Our results revealed robust differences between modalities and languages. We summarize these below.

Morphological processing across modalities

The first goal of our study was to test the hypothesis that morphological processing may be more prominent in the visual than in the auditory modality. Our results support this hypothesis, as evidenced by significant Stem-by-Modality and Suffix-by-Modality interactions (Figures 1 and 2). Accordingly, the size of the stem and suffix effects was medium in the visual modality, but small in the auditory modality. More specifically, our findings show that the presence of a stem or a suffix made it more difficult to reject a nonword in lexical decision, and that this difficulty was greater in the visual than in the auditory domain. This suggests that stems and suffixes were more rapidly identified and mapped onto existing morphemic representations in the visual modality than in the auditory modality, presumably because morphological units tend to be marked in written language, which is not necessarily the case in spoken language.

Morphological processing across languages

We also investigated whether morphological processing is modulated by the morphological productivity of a language. On the assumption that German is more morphologically productive than French (e.g., Juola, 2008; Kettunen, 2014; Sadeniemi et al., 2008), we hypothesized that morphological processing effects would be greater in German than in French. Our results revealed a significant Language-by-Stem interaction, showing that stem processing was more robust in German. Accordingly, the size of the stem effect was medium in German, but small in French. This finding was further supported by a three-way interaction between Language, Stem, and Modality, which was significant both in terms of RTs and accuracy (Figures 1 and 2). Indeed, in terms of RTs, the size of the stem effect in the visual compared to the auditory modality was medium in German, but small in French. The significantly larger stem effect in German indicates that German speakers are more proficient in rapidly extracting embedded stems, and this is particularly robust in the visual domain. Our data thus suggest that the lexical system benefits from repeated exposure to morphological regularities, as is the case in morphologically productive languages like German. We speculate that due to the productivity of its compounding system, stem extraction is more efficient in German.[4]

Differences in stem and suffix processing

One question that arises from the present findings is whether the identification of stem morphemes and affixes is based on the same core processing mechanisms, or whether the two types of morphemes have an entirely different status in the word recognition system. The first option is that the processing of stems and affixes is governed by the same morphological chunking mechanism, but that the efficiency of this mechanism is determined by how frequently

[4] It is worth noting that in a recent cross-linguistic study that investigated morphological effects on reading aloud as a function of the orthographic consistency and morphological complexity of a language (Mousikou et al., 2020), we observed that it is the orthographic consistency of a language, rather than its morphological complexity, that influences morphological processing in reading aloud. However, the consistency with which letters in a certain language map onto phonemes is critical for reading aloud, which could explain why this particular language characteristic influenced morphological processing in this task over and above morphological complexity.

stems and suffixes are used within a specific language context. This is in line with theories suggesting that morphologically complex words (e.g., *farmer*) are initially “decomposed” and mapped onto specialized morphemic representations (e.g., the stem *farm* and the suffix *-er*), which are then in turn used to generate the combined meaning of the whole word (e.g., Baayen & Schreuder, 1999; Beyersmann, Coltheart, & Castles, 2012; Crepaldi, Rastle, Coltheart, & Nickels, 2010; Diependaele, Sandra, & Grainger, 2009; Taft, 2003). However, on the assumption that stems and affixes are handled by the same kind of decompositional mechanism and are therefore closely associated, it is more difficult to explain why the observed cross-linguistic differences were only found for stems and not for suffixes.

The alternative option is based on a more recent proposal by Grainger and Beyersmann (2017) who argued that stems and suffixes are processed in different ways. While affixes always occur in combination with a stem morpheme, stems can occur as free-standing lexical units and therefore do not require setting up any specialized morphological representations (see also Beyersmann & Grainger, 2018). As such, stems can be activated simply by mapping embedded stems onto existing whole-word representations in the lexicon. This idea finds support in recent evidence from masked priming data in the lexical decision task, showing that embedded stems are rapidly activated independently of whether they are accompanied by a suffix or a non-morphemic ending (e.g., Beyersmann, Casalis, Ziegler, & Grainger, 2015; Beyersmann, Cavalli, Casalis, & Colé, 2016; Beyersmann et al., 2018; Hasenäcker, Beyersmann, & Schroeder, 2016; Heathcote, Nation, Castles, & Beyersmann, 2018; Morris, Porter, Grainger, & Holcomb, 2011; Taft, Li, & Beyersmann, 2018). Suffixes on the other hand require a specialized chunking mechanism by which they are identified and removed from the remaining input signal. The identification of an affix then sends in turn an activation boost to the embedded stem, which explains why masked priming studies with affixed and pseudo-affixed words (e.g., Longtin et al., 2003; Rastle & Davis, 2008; Rastle et al., 2004) typically show more priming to their embedded stems (e.g., *farmer-farm* and *corner-corn*) than non-affixed control words (e.g., *cashew-cash*). On the assumption that stems and affixes are handled by two entirely different mechanisms, this theoretical framework is in a better position to explain the presence of a significant Language by Stem interaction (i.e., a bigger stem effect in German than in French) in the absence of a significant Language by Suffix interaction. Stem-stem combinations form a central component of the German lexical system due to the productivity of the compounding system. Repeated exposure to compound words would then lead to the development of an efficient routine for mapping embedded stems onto existing representations in the mental lexicon, while leaving the affix-chunking mechanism unaffected. Hence, Grainger and Beyersmann's (2017) theoretical framework provides an explanation for the present findings.

Limitations and directions for future research

The results revealed a main effect of modality, showing that responses were overall slower in auditory than in visual lexical decision. While the visual system can perform a quick initial form-based analysis of the letter string, the seriality of the spoken input imposes a minimal time for word identification. A key follow-up of the current investigation would therefore be the examination of prefixed nonwords, to determine whether modality differences are present when the seriality of the stem and the affix is reversed. Moreover, the fact that German is characterized by a particularly productive compounding system, combined with the here reported evidence for a more robust stem-effect in the German language, makes the additional prediction that compound segmentation effects should be more robust in German than in French. Such prediction remains to be tested in future research.

The main effect of language was also significant, showing that German participants responded overall faster than French participants, and so was the language-by-modality interaction, indicating greater language differences in the visual modality. French has less consistent print-to-sound and sound-to-print mappings than German (Ellis et al., 2004; Seymour, Aro, & Erskine, 2003). Thus, differences in response latencies between the two samples could be due to the substantial number of silent letters in the French nonwords (compare number of letters to number of phonemes for French in Table 2). The presence of silent letters in the French nonwords would likely increase the uncertainty of print-to-sound and sound-to-print mappings in this language, thus slowing down decision times in the French sample. To further test the robustness of language and modality differences, and to further examine the influence of print-to-sound and sound-to-print consistencies on morphological processing, future research should seek to extend the current investigation to languages that provide a better match in terms of orthographic transparency (e.g., German vs. Italian).

Finally, due to the selection of translation-equivalent stems and suffixes, the French and German nonwords could not be fully matched on number of letters, number of phonemes, and OLD20. Although we took these differences into account in our analyses, future experiments should aim for selecting cross-linguistic stimuli that are fully matched on such variables.

Conclusion

The present work provides a broader cross-modality and cross-linguistic perspective on the mechanisms involved in morphological processing. The greater impact of morphology within the written modality suggests that adults benefit from morphological knowledge during reading, whereas the impact of morphological structure on spoken language processing is weaker. Moreover, the observed cross-linguistic differences in morphological processing demonstrate that language-specific characteristics can influence the cognitive mechanisms underlying visual and auditory word recognition.

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Appendix. Items used in the study.

Nonwords			
Stem+Suffix		Stem+Non-Suffix	
French	German	French	German
brasable	Armbar	brasaste	Armucht
arbrement	Baumkeit	arbrelot	Baumarf
jambeable	Beinbar	jambelot	Beinatz
balaiment	Besenkeit	balailot	Besenau
liteur	Better	literge	Bettarf
foudrement	Blitzkeit	foudrenule	Blitzpern
sangeux	Bluthaft	sangonne	Blutam
lettrement	Briefkeit	lettrenule	Briefmen
paineux	Brothaft	painache	Brotarf
seineur	Bruster	seinate	Brustekt
busion	Busung	busuque	Busarf
toiteur	Dacher	toitipe	Dachpfen
glacable	Eisbar	glacenule	Eismen
champeux	Feldbar	champonne	Feldatz
filmeux	Filmhaft	filmuque	Filmarf
volment	Flugkeit	volige	Flugucht
halleux	Flurbar	hallache	Flurpern
facement	Gesichtkeit	facenure	Gesichtarf
fantômement	Gespenstkeit	fantômenule	Gespenstpern
arrêtment	Haltkeit	arrêtipe	Haltarf
boision	Holzung	boisipe	Holzat
pouletable	Huhnbar	pouletème	Huhnam
chienion	Hundung	chienaste	Hundat
biscuitable	Keksbar	biscuitil	Keksmen
garsable	Kerlbar	garsare	Kerlmen
têtement	Kopfkeit	têtelot	Kopfekt
troument	Lochkeit	trounure	Lochucht
airement	Luftkeit	airenure	Luftucht
sourisment	Mauskeit	sourisisse	Mauspern
laitment	Milchkeit	laitope	Milcharf
lunement	Mondkeit	lunelot	Mondatz
nuiteur	Nachter	nuiterge	Nachtatz
nidion	Nestung	nidil	Nestarf
parcable	Parkbar	parcache	Parkarf
chevalion	Pferdung	chevalème	Pferdam
pointment	Punktkeit	pointerge	Punktam
rouement	Radkeit	rouenure	Radam
droiteux	Rechtbar	droitate	Rechtmen

jusion	Saftung	jusache	Saftmen
sablion	Sandung	sablenule	Sanducht
trésorion	Schatzung	trésorisse	Schatzarf
sension	Sinnung	sensare	Sinnau
pistement	Spurkeit	pistenure	Spurnauf
pierrement	Steinung	pierrenule	Steinam
fronteux	Stirnbar	frontaste	Stirnatz
jourable	Tagbar	jourouse	Tagucht
tapisable	Teppichbar	tapisisse	Teppichatz
tablement	Tischkeit	tablenure	Tischarf
poteux	Topfbar	potare	Topfekt
tunnelion	Tunnelung	tunnelipe	Tunnelau
mureux	Wandbar	muruque	Wandekt
mondement	Weltkeit	mondenure	Weltekt
ventable	Windbar	venterge	Winducht
blaguement	Witzkeit	blaguipe	Witzarf
loupeux	Wolfhaft	loupouse	Wolfat
motieux	Worthaft	motige	Wortpern
denteur	Zahner	dentaste	Zahnarf
tempsable	Zeitbar	tempsouse	Zeitam
tentement	Zeltkeit	tentenure	Zeltat
traineux	Zughaft	trainaste	Zugat

Non-Stem+Suffix		Non-Stem+Non-Suffix	
French	German	French	German
brusable	Arfbar	brusast	Arfucht
aubrement	Baufkeit	aubrelot	Baufarf
jombeable	Beunbar	jombelot	Beunatz
bavaiment	Belenkeit	bavailot	Belenau
lateur	Botter	laterge	Bottarf
foidrement	Blatzkeit	foidrenule	Blatzpern
sargeux	Blethaft	sargonne	Bletam
lottrement	Bliefkeit	lottrenule	Bliefmen
paimeux	Bromhaft	paimache	Bromarf
seifeur	Bluster	seifate	Blustekt
bumion	Bumung	bumuque	Bumarf
taiteur	Ducher	taitipe	Duchpfen
glatable	Eusbar	glatenule	Eusmen
chalpeux	Faldbar	chalponne	Faldatz
falmeux	Filthaft	falmuque	Filtarf
vosment	Fluskeit	vosige	Flusucht
holleux	Flerbar	hollache	Flerpern
ficement	Gosichtkeit	ficenure	Gosichtarf
fastômement	Gestenstkeit	fastômenule	Gestenstpern
arvêtment	Holtkeit	arvêtipe	Holtarf

boimion	Holmung	boimipe	Holmat
pauletable	Hehnbar	pauletème	Hehnam
chionion	Hondung	chionaste	Hondat
bisfuitable	Kelsbar	bisfuitil	Kelsmen
garpable	Kertbar	garpare	Kertmen
têrement	Korfkeit	têrelot	Korfekt
traument	Lechkeit	traunure	Lechucht
aipement	Luptkeit	aipenure	Luptucht
sourifment	Maunkeit	sourifisse	Maunpern
lautment	Mulchkeit	lautope	Mulcharf
luvement	Moldkeit	luvelot	Moldatz
naiteur	Nechter	naiterge	Nechtatz
nedion	Nostung	nedil	Nostarf
parmable	Parmbar	parmache	Parmarf
chetalion	Pfeldung	chetalème	Pfeldam
poiltment	Pulktkeit	poilterge	Pulktam
rauement	Ridkeit	rauenure	Ridam
draiteux	Rachtbar	draitate	Rachtmen
julion	Saktung	julache	Saktmen
satlion	Sardung	satlenule	Sarducht
trisorion	Schetzung	trisorisse	Schetzarf
selpion	Sintung	selpare	Sintau
pisfement	Smurkeit	pisfenure	Smurnauf
piurrement	Steunung	piurrenule	Steunam
fronseux	Stirmbar	fronsaste	Stirmatz
jaurable	Tafbar	jaurouse	Tafucht
tupisable	Teplichbar	tupisisse	Teplichatz
teblement	Teschkeit	teblenure	Tescharf
pomeux	Tolfbar	pomare	Tolfekt
tunfelion	Tunfelung	tunfelipe	Tunfelau
muleux	Wardbar	muluque	Wardekt
monpement	Woltkeit	monpenure	Woltekt
veltable	Wisdbar	velterge	Wisducht
bleguement	Wetzkeit	bleguipe	Wetzarf
loufeux	Wolphaft	loufouse	Wolpat
mapieux	Wosthaft	mapige	Wostpern
dunteur	Zuhner	duntaste	Zuhnarf
telpsable	Zeilbar	telpsouse	Zeilam
tenfement	Zelpkeit	tenfenure	Zelpat
praineux	Zighaft	prainaste	Zigat

Words			
Morphologically simple		Morphologically complex	
French	German	French	German
fourmi	Ameise	boulanger	Bäcker
asphalte	Asphalt	traitement	Behandlung
banane	Banane	décision	Bescheid
basilic	Basilisk	serviteur	Diener
coutume	Brauch	stupidité	Dummheit
brosse	Bürste	existence	Existenz
diamant	Diamant	forteresse	Festung
douche	Dusche	pêcheur	Fischer
succès	Erfolg	chercheur	Forscher
flamme	Flamme	liberté	Freiheit
girafe	Giraffe	coiffure	Frisur
guitare	Gitarre	jeunesse	Jüngling
auberge	Herberge	maladie	Krankheit
collègue	Kollege	artiste	Künstler
commode	Kommode	puissance	Leistung
contact	Kontakt	clairière	Lichtung
contrôle	Kontrolle	menteur	Lügner
concert	Konzert	directeur	Manager
griffe	Kralle	humanité	Menschheit
perruque	Perücke	musicien	Musiker
flaque	Pfütze	beauté	Schönheit
plaque	Platte	sécurité	Sicherheit
puzzle	Puzzle	règlement	Siedlung
pyramide	Pyramide	gagnant	Sieger
soldat	Soldat	joueur	Spieler
cigogne	Storch	position	Stellung
talent	Talent	viseur	Sucher
tomate	Tomate	entraîneur	Trainer
triomphe	Triumph	formation	Training
cigare	Zigarre	sagesse	Weisheit