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Investigating Developmental Trajectories of Morphemes as Reading Units in German

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The developmental trajectory of the use of morphemes is still unclear. We investigated the emergence of morphological effects on visual word recognition in German in a large sample across the complete course of reading acquisition in elementary school. To this end, we analyzed lexical decision data on a total of 1,152 words and pseudowords from a large cross-sectional sample of German children from the beginning of Grade 2 through 6, and a group of adults. We expand earlier evidence by (a) explicitly investigating processing differences between compounds, prefixes and suffixes, (b) taking into account vocabulary knowledge as an indicator for interindividual differences. Results imply that readers of German are sensitive to morphology in very early stages of reading acquisition with trajectories depending on morphological type and vocabulary knowledge. Facilitation from compound structure comes early in development, followed by facilitation from suffixes and prefixes later on in development. This indicates that stems and different types of affixes involve distinct processing mechanisms in beginning readers. Furthermore, children with higher vocabulary knowledge benefit earlier in development and to a greater extent from morphology. Our results specify the development and functional role of morphemes as reading units.

Keywords: reading development, morphology, word recognition, vocabulary knowledge

Many languages feature a high amount of morphologically complex words (e.g., *readable*) that are built by a combination of two or more constituent morphemes (e.g., *read* + *able*). In the field of reading acquisition, it has been theoretically suggested and empirically demonstrated that children start using morphemes as functional units in the course of reading development. At present, however, it remains unclear—both from a theoretical and from an empirical perspective—when and how exactly children become sensitive to morphology. To fill this research gap, we adopted a comprehensive approach with participants from the complete range of reading development. Hence, we examined morphological reading in German children from Grade 2 through Grade 4 and 6, with groups both at the beginning and end of each school year. Lexical decision data for 1152 words and equally many pseudowords from the *Developmental Lexicon Project* (*DeveL*; Schröter & Schroeder, 2016) were analyzed with regard to their morphological status. We explicitly compared compounds, that is words built by the combination of two stems (e.g., *cook* + *book*), and prefixed and suffixed derivations, that is words consisting of a stem and an affix either preceding or following the stem (e.g., *un* + *learn*, *read* + *able*). This allowed differentiating the relative role of stems and different types of affixes in word recognition. Also, vocabulary knowledge was taken into account as an indicator for interindividual differences, which can be considered at least equally important to age as a factor in development. By taking this extensive approach, we delineate the developmental course of morpheme use in learning to read, giving valuable new insights about the nature of different morphemes as units in word recognition. This is of interest to advance models of reading development with respect to morphological processing.

For skilled adult readers, morphemes have been extensively discussed as functional units of word recognition (for a review see Amenta & Crepaldi, 2012). Accumulated evidence suggests that morphologically complex words are parsed into their constituent morphemes. Some accounts of morphological processing in adult readers assume an obligatory sublexical decomposition of all words by means of detection of the affix, known as affix-stripping (e.g., Taft & Forster, 1975). Most support has been put forward in favor of hybrid models, which suggest that lexical access is possible both via a whole-word route and a decompositional route (e.g., Caramazza, Laudanna, & Romani, 1988; Libben, 2006; Schreuder & Baayen, 1995; Taft, 1994), with whole-word access being the default for known words and decomposition helping out in the reading of novel words.

Developing readers often encounter certain words for the first time in print. Those words cannot be retrieved from the orthographic lexicon because they do not have an entry yet: their orthographic form is not stored, because the printed form has simply not been experienced before. Thus, to read those words for the first time, smaller units need to be considered, such as graphemes, so that the word can be decoded letter-by-letter using grapheme-phoneme conversion (GPC) rules. Even in languages

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with straightforward GPC rules, this is rather time and resource consuming. The majority of new words that children encounter during their school years are morphologically complex, as Nagy and Anderson (1984) note, made up of two or more morphemes (see also Anglin, 1993). This is particularly true for German (Segbers & Schroeder, in press). More important, morphemes are units that reoccur in different combinations and, therefore, might have been encountered by children in another context before. Breaking down complex words into their morphemes thus may aid the reading of new combinations. Knowledge of morphemes, as parts of complex words, and the operations by which they can be combined, has been found to play an important role with regard to semantics by helping to break down and understand the meaning of unknown words in word definition tasks (i.e., Bertram, Laine, & Virkkala, 2000). Using known morphemes to decode unknown words has been proposed as a reading strategy for children to recognize familiar words fast and efficiently.

Complex Word Recognition in Reading Development

Most theories of reading development assume morphology to play a role at some point (e.g., Seymour, 1997), but they do not make more explicit assumptions about how morphology comes about to be used in word recognition. One theory that more explicitly includes the emergence of an access mechanism via morphemes is the multiple-route model by Grainger and Ziegler (2011). This model predicts that beginning readers start out with serial letter identification based on phonology and GPC rules and increasingly advance to more parallel orthographic processing. For orthographic processing, the model comprises two routes that both feed into whole-word orthographic representations: a fine-grained and a coarse-grained route. The fine-grained route uses location-specific coding of letter sequences. These letter sequences are intermediate-sized linguistic units, such as affixes. The fine-grained route thus entails a sublexical morphological decomposition mechanism that depends on affix detection and feeds forward activation to whole-word orthographic representations. The coarse-grained mode operates independent of specific letter position information and is more holistic in nature, but also feeds into whole-word orthographic representations. Activation at the orthographic level in turn gains from top-down feedback from semantics. More important, with the fine-grained and coarse-grained route, the multiple-route model entails a distinction similar to the decompositional route and whole-word route in hybrid models of skilled morphological processing (e.g., Caramazza et al., 1988; Diependale, Sandra, & Grainger, 2009). From a developmental perspective, the multiple-route model hypothesizes that children start to use affixes as units in reading as they advance from phonological decoding to using letter sequences in the fine-grained route. The authors suggest that this advancement marks an important shift to parallel processing of letters, which is not only important for holistic processing once a coarse-grained route becomes established, but already for the detection of affixes, especially suffixes at word endings, in the fine-grained route. As an empirical consequence, the model predicts that the development of fine-grained processing should manifest in increased sensitivity to morphological structure.

A growing number of studies have investigated the use of morphology in learning to read by comparing reading accuracy and speed of words with or without a morphological structure. This research has shown that the presence of a root or a suffix in a word speeds up lexical decision in French 3rd-, 4th-, and 5th-graders (Casalis, Quémart, & Duncan, 2015; Quémart, Casalis, & Duncan, 2012). While 4th-graders benefit from the co-occurrence of root and suffix, it might cause additional computational costs for 3rd-graders. Suffixes have also been reported to increase speed and accuracy of word naming in young Italian readers (Grade 2–3) and poor readers from Grade 6 (Burani, Marcolini, De Luca, & Zoccolotti, 2008; Marcolini, Traficante, Zoccolotti, & Burani, 2011), while skilled 6th-graders only benefit from suffixes in the case of low frequency words, and adults not at all.

Many studies with children also utilize complex *pseudowords* that are usually built by combining an existing suffix with a pseudostem or with an existing stem to form a nonexistent combination. The idea behind this is that pseudowords parallel the reading of words that have never been encountered before and cannot be accessed via a whole-word route, making them especially prone to morphological decomposition. The presence of an existing affix or stem makes pseudoword rejection more difficult for French Grade 3 and 5 readers (Casalis et al., 2015; Quémart et al., 2012). For Italian Grade 3 to 5 children, the case is less clear, as Burani, Marcolini, and Stella (2002) found rejection of affixed pseudowords being more error-prone but faster, which might also be driven by a speed–accuracy trade-off. Naming tasks also show that reading aloud is faster and more accurate for affixed pseudowords (composed of an existing stem and affix in a new combination or a pseudostem and a real affix) than monomorphemic pseudowords (Italian: Angelelli, Marinelli, & Burani, 2014; Burani et al., 2002; Burani et al., 2008; French: Colé, Bouton, Leuwers, Casalis, & Sprenger-Charolles, 2012).

Taken together, the evidence provided so far speaks in favor of a role for morphology to emerge in the elementary school years, in line with the predictions of the multiple-route model. However, the studies addressed above have investigated different groups of children: the participants were of certain selected age or skill groups, or were special populations, such as poor or dyslexic readers. This makes it hard to make coherent assertions about the developmental trajectory. Furthermore, the research has emphasized reading aloud, albeit silent reading is very common even for young readers and even more throughout development (see Nation, 2009). Reading aloud might reinforce a sequential decoding strategy in analogy to the sequential nature of the required oral output. Lexical decision can instead be expected to tap more directly into orthographic processes already in children (Nation & Cocksey, 2009), and this is more relevant to gain a thorough understanding of morphology in reading development because morphological effects are typically considered to arise in orthographic stages of processing (Diependale et al., 2009). Further, previous studies have concentrated on suffixed derivations, neglecting prefixed derivations and compounds. Basically all the above described studies have concentrated on suffixed derivation, while studies examining prefixed derivations and compounds are sparse and use deviating paradigms or methodologies. For example, prefix identification in Dutch 3rd- and 6th-graders was examined by Verhoeven, Schreuder, and Haarman (2006) with a different manipulation and compound reading was studied in Finnish 1st- and 2nd graders by Häikiö, Bertam, and Hyönä (2011) using eye-tracking of hyphenated and concatenated compounds in sentence contexts.

To our knowledge, no lexical decision or naming experiments as the ones described above have been undertaken with prefixed and compounded words and pseudowords. This is surprising, because those morphological types are also very common in many languages. To gain a thorough understanding of the role of morphology in reading, it is necessary to examine the processing of all morphological types. This would allow to more precisely test the assumptions about affix detection and parallel processing in the fine-grained route of the multiple-route model.

Overall, the developmental evidence remains fragmented both with regard to participants and to items. Yet, to truly understand the evolvement of morphology effects in reading development, it is crucial to examine children across the range of reading acquisition and the various morphological types.

Preferences for Morphological Types

As mentioned above, distinct morphological types need to be taken into consideration when examining morpheme use in reading development, specifically the differences between prefixes and suffixes have been neglected. From a linguistic perspective, prefixes and suffixes are rather distinct with regard to their semantic function, their ability to alter phonological or orthographic form and their ability to change the syntactic category of the word. Cross-linguistically, there is a preference for languages to have predominantly suffixes rather than prefixes (Cutler, Hawkins, & Gilligan, 1985). Cutler et al. (1985) argue that this suffix preference reflects principles of lexical processing. Especially, it is attributed to a left-to-right processing bias, which goes hand-in-hand with a preference for the stem as the most informative part favoring the most salient position, that is, the first (or the left-most) position. Under this assumption, suffixed words can be immediately activated via the stem, whereas identification of the stem in prefixed words needs to be delayed until the rest of the word is recognized. As a consequence, distinct mechanisms could be involved in processing prefixes and suffixes, as corroborated by psycholinguistic studies with skilled adult readers (e.g., Bergman, Hudsonxs, & Eling, 1988; Beyersmann, Ziegler, & Grainger, 2015; Colé, Beauvillain, & Segui, 1989; but see Gonnerman, Seidenberg, & Andersen, 2007). For children, especially in the early phases of reading development, a preference for suffixed words, which have the stem as the more informative part in the beginning, can be predicted, since the left-to-right processing bias is particularly pronounced in beginning readers (Bertram & Hyönä, 2003). However, this stands in contrast to the parallel nature of the affix detection assumed by the multiple-route model (Grainger & Ziegler, 2011). As evidence on prefixes in children's visual word recognition is extremely sparse (but see Verhoeven et al., 2006), it is unclear whether prefixes and suffixes emerge as reading units at the same time or whether they exhibit different developmental trajectories. As a consequence, a systematic and direct comparison of the processing of prefixed and suffixed words in reading development across the elementary school years is urgent. Additionally, it is important to include compounds into the scope of developmental studies on complex words. As compounds are built of two stems, they enable to test morphological effects in the absence of affixes, giving further insight into the mechanisms underlying the emerging ability to extract stems in reading development.

Vocabulary Knowledge in Complex Word Reading

The importance of vocabulary knowledge for reading and reading development has been emphasized by various theoretical accounts (e.g., Harm & Seidenberg, 2004; Perfetti & Hart, 2002). Good vocabulary knowledge is associated with high-quality lexical representations that are important building blocks of reading. Individuals with high levels of vocabulary knowledge usually entertain good representations not only of free stems but also bound morphemes (Reichle & Perfetti, 2003). In their framework of morphological processing, Schreuder and Baayen (1995) hypothesize that experience with morphologically complex forms and with single constituent morphemes supports the detection of form-meaning consistencies, which allows developing morphemic representations at the access level. Thus, if a person encounters a complex word (e.g., *priceless*), access of this word is thought to be supported by previous experience with the whole form itself (*priceless*), as well as the stem (*price*), the affix (*less*), and forms sharing the same stem (e.g., *pricy*, *pricetag*) or the same affix (e.g., *nameless*, *speechless*). Thus, knowledge of morphemes or morphological relatives endorses the recognition of complex words (Reichle & Perfetti, 2003). Carlisle and Fleming (2003) provide evidence that knowledge of full forms, stems, and affixes influences the development of morphological processing, as does knowledge of morphological relatives (Carlisle & Katz, 2006; Goodwin, Gilbert, Cho, & Kearns, 2014). Furthermore, for skilled adult readers recent work has made a case for vocabulary being associated with differences in the manner and/or extent of morphological decomposition (Andrews & Lo, 2013). Consequently, interindividual differences in vocabulary knowledge can be expected to have a significant impact over and above grade on the developmental trajectory of morphemes as reading units.

The Present Study

The aim of the present study is to provide a comprehensive examination of the use of morphemes in word recognition across reading development. To this end, we analyze lexical decision data from nine groups of participants, including Grade 2 through Grade 4 and Grade 6 students, with groups of children both at the beginning or end of each school year, as well as adults; thus, covering the whole range of reading development in the elementary school years. This allows comparing the developmental trajectories of the influence of different types of morphemes on word recognition for children at different stages in reading development. In contrast to previous studies, we use the extensive lexical decision database from the *DeveL* project (Schröter & Schroeder, 2016), comprising many words with a great range of characteristics. Using a large unmatched item set has the advantage that many item characteristics can be statistically accounted for without severely limiting the representativeness of the item set (Baayen & Milin, 2010). Such an approach has been repeatedly shown to present a powerful and valuable way of investigating word recognition processes (for a review see Balota, Yap, Hutchison, & Cortese, in press). Using this approach, we compare responses to compounds, derived, and monomorphemic words and pseudowords. Additionally, we investigate two related issues that are relevant to move the debate about morphemes as functional units in word recognition forward: (a) differential processing of distinct morphological types and (b) the influence of interindividual differences in vocabulary knowledge on the developmental trajectory.

Based on previous studies on morphology in reading development and on the observation that comprehension of derived words substantially increases between Grade 3 and 5 (Anglin, 1993; Segbers & Schroeder, in press), we expect that morphemic structure benefits word recognition in German in Grade 3 at the latest, possibly even earlier, after an initial stage of letter-by-letter decoding has been accomplished. In the framework of the multiple-route model, which suggests morphological decomposition by detection of the affix in a parallel fashion, effects from prefixed and suffixed derivations should arise at the same time, and effects of compounds, which do not feature an affix, should arise later in development. In contrast, under the assumption of a left-to-right bias and a stem preference, effects from compounds can be suspected to arise earliest in the course of reading development, as they consist of two stems, which are the more informative units for lexical decision. Furthermore, assuming a left-to-right processing bias and a preference for stems, effects from suffixed derivations should arise in an earlier developmental phase than effects from prefixed derivations. Finally, we anticipate that vocabulary knowledge moderates the ability to utilize morphemes in reading development over and above grade, with better vocabulary knowledge being associated with a greater benefit from morphology, as suggested by the framework of Schreuder and Baayen (1995; see also Reichle & Perfetti, 2003).

Method

Participants

The analyses in this study present archival post hoc analyses of data that was attained within the framework of the *DeveL*, a large-scale cross-sectional study on word recognition across the life span (Schröter & Schroeder, 2016). Elementary schoolchildren attending Grade 2 through 4 and Grade 6 were recruited and tested during regular school hours at their schools in the Berlin area. For each grade, one group of children was tested at the beginning of the school year and another group of children was tested at the end of the school year. In addition, data was collected from students from the Berlin universities. Participant characteristics are summarized in Table 1.

All participants completed a reading fluency test (the SLS 1–4 in Grades 2–4 and the SLS 5–8 in Grade 6 and in adults; Auer, Gruber, Mayringer, & Wimmer, 2005; Mayringer & Wimmer, 2003), indicating that overall each of the subgroups had reading skills typical for their respective age group (all $t < 2$, all $p > .05$; norms for adults were derived from norm data for Grade 8). Moreover, individual differences in vocabulary knowledge were assessed with a vocabulary test (the vocabulary subtest of the CFT-20R; Weiß, 2006).

Materials

The material used in the *DeveL* project comprised 1,152 German words (768 nouns, 269 verbs, and 115 adjectives) taken from the *childLex* corpus (Schroeder, Würzner, Heister, & Geyken, 2014). Word length ranged from 3 to 12 letters ($M = 6.0$, $SD = 1.81$). Word frequency, as referring to base 10 log-transformed normalized lemma frequency, ranged from −0.99 to 3.81 ($M = 1.61$, $SD = 0.69$). Morphological status was manually determined. Words consisting of only one stem (e.g., *Laterne*, engl. lantern) were marked as monomorphemic (M). Words made up by the combination of two stems (e.g., *Segelboot*, engl. sailboat) were categorized as compounds (C). Words with a stem and at least one derivational affix (e.g., *Lehrer*, engl. teacher) were classified as derivations (D). Derivations were further subdivided into prefixed (*Pre*) and suffixed (*Suf*) words. In total, there were 959 monomorphemic words, 49 compounds and 144 derivations, of which 75 were prefixed, 62 were suffixed, and 7 contained both a prefix and a suffix. For all words, additional characteristics, including orthographic neighbors, bigram frequency, imageability, and age of acquisition were available. Those word characteristics are summarized per morphological type in Table 2.

The lexical-decision task additionally comprised 1,152 pseudowords that were generated from words using the pseudoword generator Wuggy (Keuleers & Brysbaert, 2010). All resulting pseudowords were pronounceable and matched the words on length and capitalization, because German nouns are always capitalized. For a subset of the pseudowords, morphological structure was preserved. As for the words, morphological status was determined manually for the pseudowords. Pseudowords consisting of a pseudostem only (e.g., *Kompire*) were characterized as being monomorphemic. Pseudowords combining a pseudostem with a real stem (e.g., *Bettdepse*, with *Bett* engl. bed) were classified as compounds. Pseudowords made up of a pseudostem and an existing affix (e.g., *Pauner*, with *-er* being roughly equivalent to the English suffix *-er*) were labeled as derivations and subdivided into prefixed and suffixed derivations. In total, there were 905 monomorphemic, 29 compound and 215 derived pseudowords, the latter of which 80 contained a prefix, 126 contained a suffix, and 9

Table 1
Overview Over Participant Characteristics: Number of Participants, Mean Age, Reading Fluency, and Vocabulary Knowledge

	Grade 2		Grade 3		Grade 4		Grade 6		
Characteristics	Beg	End	Beg	End	Beg	End	Beg	End	Adults
N	43	146	89	62	57	70	56	61	43
Mean Age	7.13	7.85	7.83	8.79	9.17	9.87	11.30	11.73	24.86
Reading Fluency[a]	18.28	28.29	33.88	40.53	41.49	45.74	34.66	37.49	61.09
Vocabulary Knowledge[b]	4.70	7.97	11.23	13.52	14.33	17.77	19.66	21.61	27.79

[a] SLS 1–4 in Grades 2 to 4, SLS 5–8 in Grade 6 and adults, normalized values ($M = 100$, $SD = 15$). [b] CFT-20R vocabulary test in Grade 2 to adults (0–30 points).

Table 2
Overview Over Item Characteristics Per Morphological Type: Mean Number of Items, Frequency, and Length

Characteristics	Compounds	Derivations		Monomorphemic
		Prefixed	Suffixed	
		Words		
N	49	75	62	959
Frequency[a]	.88 (.66)	1.16 (.76)	1.33 (.81)	1.70 (.64)
Length[b]	8.61 (1.29)	8.52 (1.19)	7.37 (1.38)	5.56 (1.55)
Neighbors[c]	3.03 (.50)	2.08 (.49)	2.16 (.47)	1.65 (.49)
Bigram[d]	109.94 (17.36)	115.90 (16.43)	98.74 (17.17)	78.35 (20.46)
Imageability[e]	5.12 (1.78)	3.77 (1.20)	4.89 (1.41)	5.22 (1.39)
Age of Acquisition[f]	5.18 (1.46)	5.77 (1.42)	5.16 (1.10)	5.18 (1.46)
		Pseudowords		
N	29	80	126	905
Length[b]	8.59 (1.50)	8.51 (1.19)	6.96 (1.39)	5.53 (1.56)
Neighbors[c]	3.39 (.65)	2.31 (.44)	2.28 (.64)	1.79 (.69)
Bigram[d]	109.82 (18.54)	115.56 (16.77)	93.52 (17.53)	76.80 (20.33)

[a] log10 transformed lemma frequency. [b] Number of letters. [c] OLD20: mean Levenshtein distance of 20 closest neighbors. [d] Summed log bigram frequencies. [e] 7-point Likert scale (1 = *very hard to image*, 7 = *very easy to imagine*). [f] In years.

contained both. Because of a matching error, three pseudowords were duplicated. Item characteristics are summarized in Table 2.

Procedure

Each participant was tested individually in a separate room at their schools or university, respectively. As described in more detail by Schröter and Schroeder (2016), stimuli of the experiment were presented on a laptop monitor in the center of a black screen in white lower case letters (28-point Courier New font). Each trial consisted of a 500-ms fixation cross, followed by the stimuli, which remained on screen until a response was made. Participants were instructed to decide as quickly and as accurately as possible whether the presented stimulus was an existing German word or not and indicate their decision by button press. Not all children were presented with all stimuli, but each child processed a subset, such that in total all stimuli were presented in each age group using a multi matrix design (see Schröter & Schroeder, 2016 for details). Each adult processed 1,152 trials, each 6th-grader 576 trials, each 4th-grader and 3rd-grader (at the end of the school year) 384 trials, each 3rd-grader (at the beginning of the school year) and each 2nd-grader 288 trials (see Schröter & Schroeder, 2016 for details). Response time and accuracy were measured. Participant and item effects can be dissociated using linear-mixed-effects models.

Results

All data analyses were performed using (generalized) linear mixed-effects models (Baayen, Davidson, & Bates, 2008) as implemented in the lme4 package (Version 1.1–6; Bates, Mächler, Bolker, & Walker, 2014) in the statistical software R. Linear mixed-effects models were chosen, because they are flexible in dealing with unbalanced data sets and variability in participants and items and provide enhanced power (Baayen et al., 2008). Words and pseudowords were analyzed separately. Reaction time (RT) data were log-transformed based on inspection of the data with the boxcox function from the MASS package and were then analyzed using a linear model. Accuracy data were logit-transformed and analyzed using a generalized linear model with a binomial link function. The overall effects tests used contrast coding and Type 3 model comparison (using the Anova function in the car package). Post hoc comparisons were carried out using cell means coding and single *df* contrasts with the glht function of the multcomp package (Hothorn, Bretz, & Westfall, 2008) and were evaluated using a normal distribution.

Words

First, we examined the responses to compounds, derived, and monomorphemic words in reading development. For analysis of the response time data, all incorrect responses were removed first (7.52%), as were response times below 200 ms (0.64%). Further outlier trimming followed Baayen and Milin (2010): a base model was fitted to the data, only including participants and items as random effects. Data points with residuals exceeding 2.5 *SD*s were removed (2.40%). For the remaining response data, we fitted a model with Morphological Type (C vs. Pre vs. Suf vs. M) and Age group (9: Grade 2, 3, 4 and 6, each at the beginning and end, vs. adults), both effect coded, and their interaction as fixed effects. Length and Frequency, as centered continuous variables, were included as control variables in interaction with Age group. Moreover, OLD20, Bigram Frequency, Imageability, and Age of Acquisition were also included as centered continuous control variables. Participants and Items served as random effects. Descriptive statistics are presented in Table 3 and an overview of the overall effects tests is shown in Table 4 (note that only those effects are presented that were of primary interest for this study).

The model yielded a significant main effect for Age group, indicating overall decreasing response times with increasing age. There was also a main effect of Morphological Type, suggesting that compounds, derivations, and monomorphemic words were responded to differently. More important, Morpho-

Table 3
Mean Response Times (Milliseconds) and Error Rates (%) to Words (SEs in Parentheses)

Morphological type	Grade 2 beg	Grade 2 end	Grade 3 beg	Grade 3 end	Grade 4 beg	Grade 4 end	Grade 6 beg	Grade 6 end	Adults
					Response times (ms)				
Compounds	3,096 (165)	1,613 (49)	1,316 (49)	1,107 (48)	1,055 (46)	892 (36)	785 (35)	694 (29)	555 (27)
Prefixed	3,104 (158)	1,687 (48)	1,404 (50)	1,152 (47)	1,140 (49)	925 (35)	801 (34)	713 (29)	555 (26)
Suffixed	3,109 (157)	1,691 (47)	1,377 (48)	1,126 (46)	1,123 (47)	921 (35)	794 (34)	708 (28)	560 (26)
Monomorphemic	3,060 (139)	1,709 (43)	1,404 (44)	1,168 (44)	1,161 (45)	961 (34)	835 (33)	733 (28)	575 (26)
					Error rates (%)				
Compounds	16.85 (3.50)	4.82 (.83)	5.02 (1.00)	2.12 (.52)	2.10 (.54)	1.19 (.33)	1.52 (.37)	1.87 (.44)	1.01 (.26)
Prefixed	12.04 (2.30)	7.30 (.99)	5.95 (.97)	3.49 (.67)	3.24 (.65)	1.96 (.41)	1.74 (.35)	2.15 (.41)	1.04 (.22)
Suffixed	14.33 (2.67)	7.28 (.97)	7.95 (1.22)	4.06 (.77)	3.02 (.63)	2.54 (.52)	2.65 (.51)	2.60 (.49)	1.34 (.28)
Monomorphemic	14.83 (1.66)	8.02 (.61)	7.86 (.72)	5.13 (.56)	4.57 (.52)	3.56 (.39)	3.24 (.37)	4.07 (.44)	2.52 (.31)

logical Type significantly interacted with Age group. To investigate this interaction, the effect of Morphological Type was analyzed for each Age group separately using post hoc contrasts with monomorphemic words as the reference category. For compounds compared to monomorphemic words, there was a significant facilitatory effect starting from the end of 2nd grade, all $t > 2.17$, all $p < .03$, while there was no such effect for readers in the beginning of 2nd grade, $t = -0.44$, $p = .66$. For prefixed words, there was a facilitatory effect starting from the end of 4th grade, all $t > 2.00$, all $p < .05$, but not before that, all $t < 1.10$, all $p > .26$. For suffixed words, there was a facilitatory effect starting from the end of 3rd grade, all $t > 2.09$, all $p < .05$, but not before that, all $t < 1.23$, all $p > .22$. Exact *t*- and *p* values for each age group and morphological type comparison are provided in the Appendix (Table A1). The effects are also presented in Figure 1.

The error data was analyzed in a similar way. A model was fitted to the error rates as described above. Paralleling the results for the response times, there was a main effect of Age group and a main effect of Morphological Type, which was qualified by the interaction of Morphological Type and Age group. For compounds, there was a facilitatory effect from the end of 2nd grade onward, all $t > 2.28$, all $p < .02$, but not at the beginning of 2nd grade, $t = -0.63$, $p = .53$. For prefixed words, the facilitatory effect emerged from the end of 4th grade onward, all $t > 2.78$, all $p < .004$, and also in the end of 3rd grade, $t = 2.14$, $p = .03$, but not in the beginning of 4th grade, $t = 1.70$, all $p = .07$, and not before the beginning of 3rd grade, all $t < 1.84$, all $p > .07$. For suffixed words, a facilitatory effect emerged in the beginning of 4th grade, end of 6th Grade, and in adults, but not for the other age groups. The effects are presented in Figure 1. Exact *t*- and *p* values are provided in the Appendix (Table A1).

The results point to morphemes as functional units in skilled and beginning reading and a differential developmental trajectory of the processing of compounds, prefixed, and suffixed derivations. There is a processing advantage for compounds already in 2nd grade. Effects are slightly different between prefixes and suffixes: facilitation in the response times emerges earlier for suffixed than for prefixed words, while the picture is less stable in the error rates. Together, the results indicate that

Table 4
Results From Mixed-Effect Models for Words With MorphType (C vs. Pre vs. Suff vs. M), Age Group (Grade (Beg/End) vs. Adults), as Well as Their Interactions, and Participant and Item as Random Intercepts

Variables	Reaction times χ^2	Reaction times *p*	Errors χ^2	Errors *p*
Fixed effects (*df*)				
Intercept (1)	239,160	<.001	1,685	<.001
Vocabulary Knowledge (1)	207	<.001	76	<.001
Age group (8)	130	<.001	229	<.001
Age group × Vocabulary Knowledge (8)	70	<.001	17	.027
Morphological Type (3)	18	<.001	37	<.001
Morphological Type × Vocabulary Knowledge (3)	255	<.001	5	.169
Morphological Type × Age group (24)	55	<.001	50	.001
Morphological Type × Age group × Vocabulary Knowledge (24)	136	<.001	34	.079
Random effects				
Participants	69,759	<.001	59,517	<.001
Items	5,881	<.001	3,310	<.001

Note. Main effects and interactions from the model additionally including vocabulary knowledge are indented. Tests are based on Type 3 sum of squares and χ^2 values with Kenward-Roger *df*.

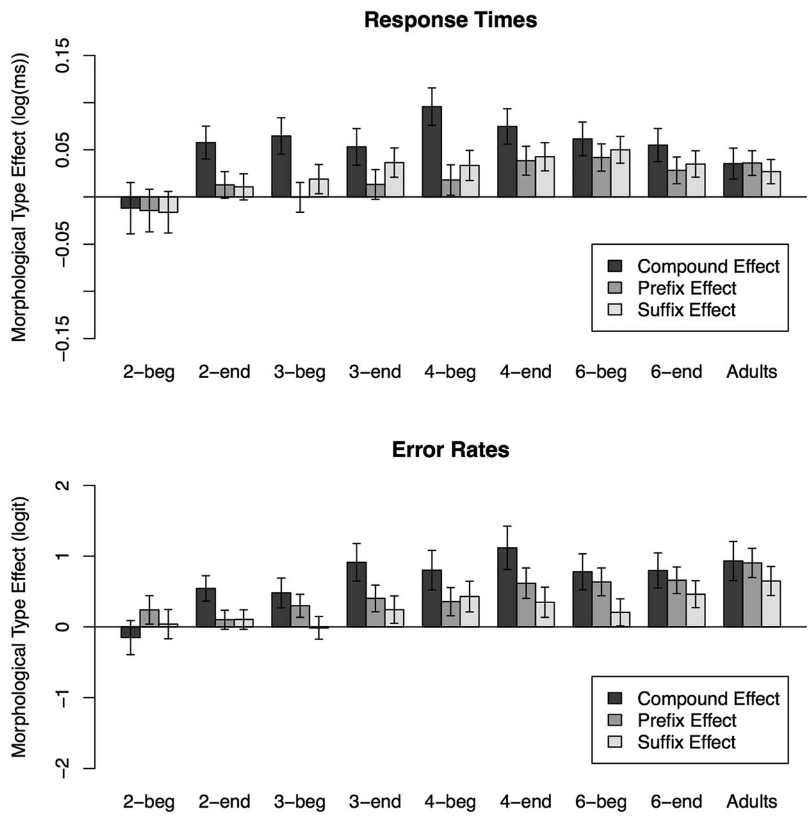

Figure 1. Response time differences (log(ms)) and Error rate differences (logit) between compounds and monomorphemic, prefixed and monomorphemic, and suffixed and monomorphemic words by Age group. Error bars show *SE*s.

different processing mechanisms are involved in the reading of compounds, prefixed, and suffixed words.

Vocabulary Knowledge. To assess interindividual differences in the use of morphemes across reading development, we analyzed how the children's vocabulary knowledge moderates the morphology effect. We fitted a model as described above, but additionally included Vocabulary Knowledge (z-transformed) as a main effect and in interaction with Age group and Morphological Type. Results of the overall effects tests are shown as indented rows in Table 4.

The model yielded a significant effect of Vocabulary Knowledge and an interaction of Vocabulary Knowledge with Age group, an interaction with Morphological Type, as well as a three-way interaction of Vocabulary Knowledge, Age group and Morphological Type. To investigate this interaction, the effect of Morphological Type was evaluated for readers with higher vocabulary scores (+1 *SD*) in each Age group and for readers with lower vocabulary scores (−1 *SD*) in each Age group using post hoc contrasts. For readers with higher vocabulary scores, there was a significant facilitatory effect for compounds from the end of 2nd grade, all $t > 2.73$, all $p < .006$, but not in the beginning of 2nd grade, $t = 1.10$, $p = .24$. For prefixed words, there was a facilitatory effect from the end of 2nd grade, all $t > 2.03$, all $p < .04$, but not in the beginning of 2nd and end of 6th grade, both $t < 1.52$, both $p > .13$. For suffixed words, there was a facilitatory effect from the end of 2nd grade onward, all $t > 2.08$, all $p < .04$, but not in the beginning of 2nd grade, $t = -0.15$, $p = .88$. For readers with lower vocabulary scores, there were no facilitatory effects for compounds in any age group, all $t < 1.92$, all $p > .05$. For prefixed words, there was an inhibitory effect in 2nd grade and in the beginning of 3rd, 4th, and 6th grade, all $t > 2.06$, all $p < .04$, and a facilitatory effect in adults, $t = 3.21$, $p = .001$, but no effect in the other age groups, all $t < 1.28$, all $p > .20$. For suffixed words, there was an inhibitory effect at the end of 2nd and beginning of 3rd grade, both $t > 2.09$, both $p < .04$, but no effect in any other age group, all $t < 1.74$, all $p > .08$. The effects for higher and lower vocabulary participants in each Age group are presented in Figure 2. Exact *t*- and *p* values are provided in the Appendix (Table A1).

A similar model was fitted to the error rates. There was a main effect of Vocabulary Knowledge, as well as an interaction of Vocabulary Knowledge and Age group, but no significant interaction with Morphological Type.

Taken together, vocabulary knowledge moderates the benefits of morphology in word recognition across reading development. Readers with better vocabulary knowledge generally show facilitation from morphology earlier in reading development. Readers with weaker vocabulary knowledge have difficulties with derivations, particularly with prefixed words.

Pseudowords

Parallel to the examination of words, we examined the responses to pseudowords that had a compound, derived, or monomorphemic

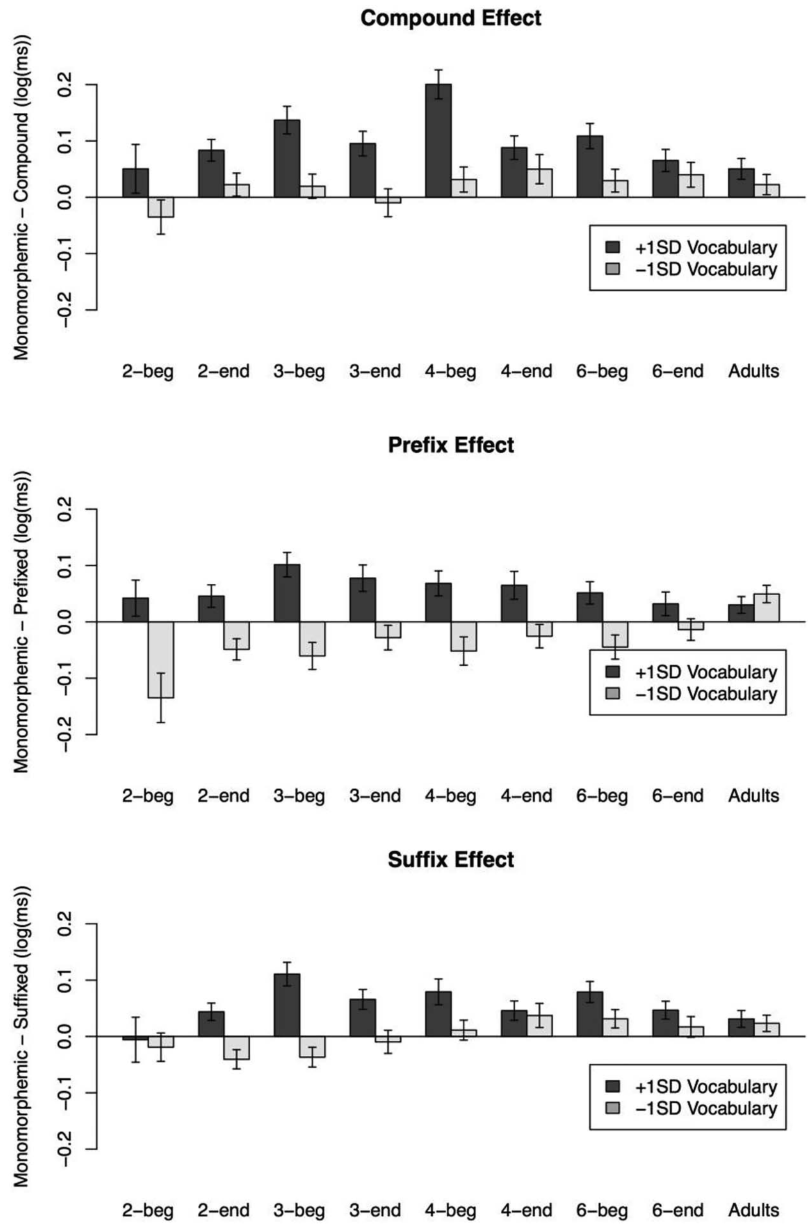

Figure 2. Compound, Prefix, and Suffix Effects for words in readers with higher (+1 *SD*) and lower (−1 *SD*) vocabulary scores by Age group. Error bars show *SE*s.

structure. As for words, all incorrect responses were removed before model fitting (11.80%), as were response times below 200 ms (0.05%). Further outlier trimming was executed by fitting a base model and removing data points with residuals exceeding 2.5 *SD*s (2.15%; Baayen & Milin, 2010). Then, we fitted a model similar to the one for words with Morphological Type and Age group and their interactions as fixed effects. Length in interaction with Age group was included as a control variable, as well as OLD20 and Bigram Frequency. Participants and Items served as random effects. Descriptive statistics are presented in Table 5 and an overview of the overall effects tests is shown in Table 6.

In the response time model, a significant main effect for Age group and Morphological Type was observed, moderated by their interaction. For pseudocompounds, there was an inhibitory effect for all age groups, all $t > 2.06$, all $p < .04$. For prefixed pseudowords, there was an inhibitory effect from the end of 3rd grade onward, all $t > 2.33$, all $p < .03$, but not before that, all $t < 1.32$, $p > .19$. For suffixed pseudowords, there was no effect in any age group, all $t < 1.84$, all $p > .07$. The effects for each Age group are presented in Figure 3. Exact *t*- and *p* values are provided in the Appendix (Table A2).

A similar model was fitted to the error data. Besides a main effect of Age group, there was a main effect for Morphological Status, but no interaction of Morphological Status and Age group. Pseudocompounds yielded significantly more errors than monomorphemic pseudowords, $t = -5.70$, $p < .001$, and so did pre-

Table 5
Mean Response Times (Milliseconds) and Error Rates (%) to Pseudowords (SEs in Parentheses)

Morphological type	Grade 2 beg	Grade 2 end	Grade 3 beg	Grade 3 end	Grade 4 beg	Grade 4 end	Grade 6 beg	Grade 6 end	Adults
					Response times (ms)				
Compounds	4,549 (303)	2,752 (99)	2,356 (105)	1,746 (90)	1,795 (96)	1,518 (73)	1,200 (63)	1,007 (51)	659 (38)
Prefixed	4,078 (243)	2,599 (84)	2,155 (88)	1,770 (86)	1,736 (88)	1,486 (67)	1,151 (57)	993 (47)	653 (37)
Suffixed	4,098 (234)	2,562 (79)	2,088 (83)	1,649 (77)	1,697 (83)	1,386 (61)	1,086 (53)	942 (44)	627 (35)
Monomorphemic	4,225 (234)	2,552 (76)	2,110 (80)	1,662 (76)	1,672 (79)	1,368 (59)	1,092 (53)	937 (43)	622 (34)
					Error rates (%)				
Compounds	30.46 (6.41)	21.21 (3.26)	24.92 (4.12)	13.54 (2.91)	16.75 (3.47)	11.26 (2.42)	13.98 (2.76)	15.41 (2.84)	5.28 (1.27)
Prefixed	18.05 (3.31)	11.66 (1.48)	10.75 (1.63)	8.58 (1.50)	7.59 (1.40)	9.42 (1.51)	8.56 (1.41)	10.56 (1.60)	2.97 (.59)
Suffixed	17.01 (2.64)	11.79 (1.19)	12.25 (1.48)	6.85 (1.03)	8.04 (1.21)	8.86 (1.20)	6.92 (1.00)	8.66 (1.17)	2.93 (.49)
Monomorphemic	15.51 (1.98)	10.92 (.85)	11.13 (1.07)	5.66 (.68)	6.47 (.80)	7.77 (.86)	6.63 (.80)	8.25 (.94)	2.50 (.36)

fixed pseudowords, $t = -2.00$, $p = .04$, while there was no effect for suffixed pseudowords, $t = 1.80$, $p = .07$.

The results suggest that morphological structure is taken into consideration by skilled and beginning readers in judging whether a letter string constitutes a real word or a pseudoword. The presence of a stem in pseudowords with a compound structure makes rejection harder already for beginning readers. The presence of a prefix has this hampering effect later on in reading development, starting in 4th grade, while suffixes do not disturb pseudoword rejection.

Vocabulary Knowledge. Parallel to the analyses of the word data, we also investigated interindividual differences in the pseudoword data. A model as described for the vocabulary knowledge analysis for words was fitted. Descriptive statistics are presented in Figure 6 and results of the overall effects tests are shown as indented rows in Table 7.

As in the results for the words, in addition to the effects found in the model without interindividual differences, a significant main effect of Vocabulary Knowledge emerged. The interactions of Vocabulary Knowledge with both Age group and Morphological Type were also significant, as was the three-way interaction of Age group, Morphological Type and Vocabulary Knowledge. For readers with higher vocabulary scores (+1 *SD*), there was an inhibitory effect for pseudocompounds from the beginning of 2nd grade onward, all $t > 2.23$, all $p < .03$, except in the end of 3rd and beginning of 4th and 6th grades, all $t < 1.67$, $p > .09$. For prefixed pseudowords, there was an inhibitory effect from the end of 2nd grade, all $t > 2.44$, $p < .01$, but not in the beginning of 2nd, 4th, and 6th grade, all $t < 1.83$, all $p > .07$. For suffixed pseudowords, there was a facilitatory effect in the end of 3rd and the beginning of 4th and 6th grade, all $t > 2.01$, all $p < .04$, but in no other age group, all $t < 1.36$, all $p > .17$.

For readers with lower vocabulary scores (−1 *SD*), there was an inhibitory effect for pseudocompounds from the end of 2nd grade, all $t > 2.14$, all $p < .03$, but not in the beginning of 2nd and end of 3rd grade, both $t < 1.89$, both $p > .07$. For prefixed pseudowords, there was an inhibitory effect from the end of 3rd grade, all $t > 2.16$, all $p > .03$, but not before this, all $t < 1.67$, all $p > .09$. For suffixed pseudowords, there was an inhibitory effect in 4th grade and the end of 6th grade, all $t > 2.64$, all $p < .008$, and no

Table 6
Results From Mixed-Effect Models for Pseudowords With MorphType (C vs. Pre vs. Suff vs. M), Age Group (Grade (Beg/end) vs. Adults), as Well as Their Interactions, and Participant and Item as Random Intercepts

Variables	Reaction times		Errors	
	χ^2	*p*	χ^2	*p*
Fixed effects (*df*)				
Intercept (1)	213,820	<.001	1059	<.001
Vocabulary Knowledge (1)	167	<.001	37	<.001
Age group (8)	111	<.001	94	<.001
Age group × Vocabulary Knowledge (8)	33	<.001	5	.710
Morphological Type (3)	38	<.001	34	<.001
Morphological Type × Vocabulary Knowledge (3)	29	<.001	6	.122
Morphological Type × Age group (8)	67	<.001	21	.628
Morphological Type × Age group × Vocabulary Knowledge (24)	91	<.001	32	.127
Random effects				
Participants	87,075	<.001	8767	<.001
Items	3,901	<.001	2616	<.001

Note. Main effects and interactions from the model additionally including vocabulary knowledge are indented. Tests are based on Type 3 sum of squares and χ^2 values with Kenward-Roger *df*.

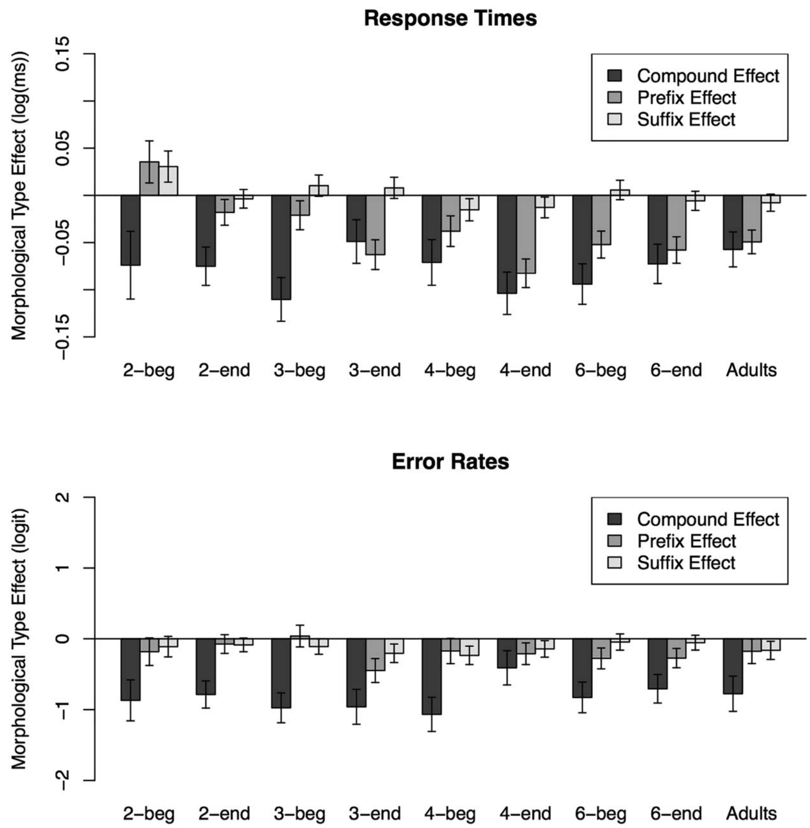

Figure 3. Response time differences (log(ms)) between compounds and monomorphemic, prefixed and monomorphemic, and suffixed and monomorphemic pseudowords by Age group. Error bars show *SE*s.

effect in the other age groups, all $t < 1.83$, all $p > .07$. The effects for higher and lower vocabulary participants in each age group are presented in Figure 4. Exact *t*- and *p* values are provided in the Appendix (Table A2).

The corresponding error rate model again only revealed main effects for Age group and Morphological Type, but neither a main effect of Vocabulary Knowledge, nor any interactions involving it.

Taken together, readers with higher vocabulary scores are generally affected by morphological structure in pseudowords in an earlier developmental phase than readers with lower vocabulary scores. Moreover, the direction of the suffix effect in pseudowords is moderated by vocabulary knowledge.

Discussion

In the present study, we analyzed lexical decision data from a large sample of children from Grade 1 through 6, covering the entire range of reading development in the elementary school years, as well as adults, to provide a comprehensive examination of the use of morphemes in word recognition across reading development in German. We compared responses to compounds, derived and monomorphemic words and pseduowords. The comprehensive approach of the present study covered the entire developmental trajectory of morphology use and demonstrates that morphemes gradually emerge as units of word recognition in the course of reading development. First effects can be observed as early as in 2nd grade and increase in the elementary school years. Moreover, our study expands existing evidence by (a) revealing differential processing of different morphological types, and (b) highlighting the influence of vocabulary knowledge on morphological processing.

The sensitivity to morphological structure that starts between Grade 2 and 4 is consistent with previous studies from transparent orthographies demonstrating effects of suffixes for words and pseudowords in naming and lexical decision (French: Casalis et al., 2015; Colé et al., 2012; Quémart et al., 2012; Italian: Angelelli et al., 2014; Burani et al., 2002, 2008; Marcolini et al., 2011). Our results demonstrate that the distinction between morphological types is important, because the developmental trajectories for compound, prefix, and suffix effects differ. In particular, including compounds shows that sensitivity to morphology emerges slightly earlier in transparent languages than previous studies were able to capture, because they focused on suffixes. An interesting find was that for words, facilitation from compounds arises already at the very early stages of reading acquisition around 2nd grade and remains an important unit of analysis throughout development in the elementary school and also for skilled adult readers. Suffix effects in words follow slightly later in the course of reading acquisition and emerge in 3rd grade, in line with findings for French 3rd-graders (Casalis et al., 2015; Quémart et al., 2012). Prefix effects emerge even slightly later. Thus, there is a sequential

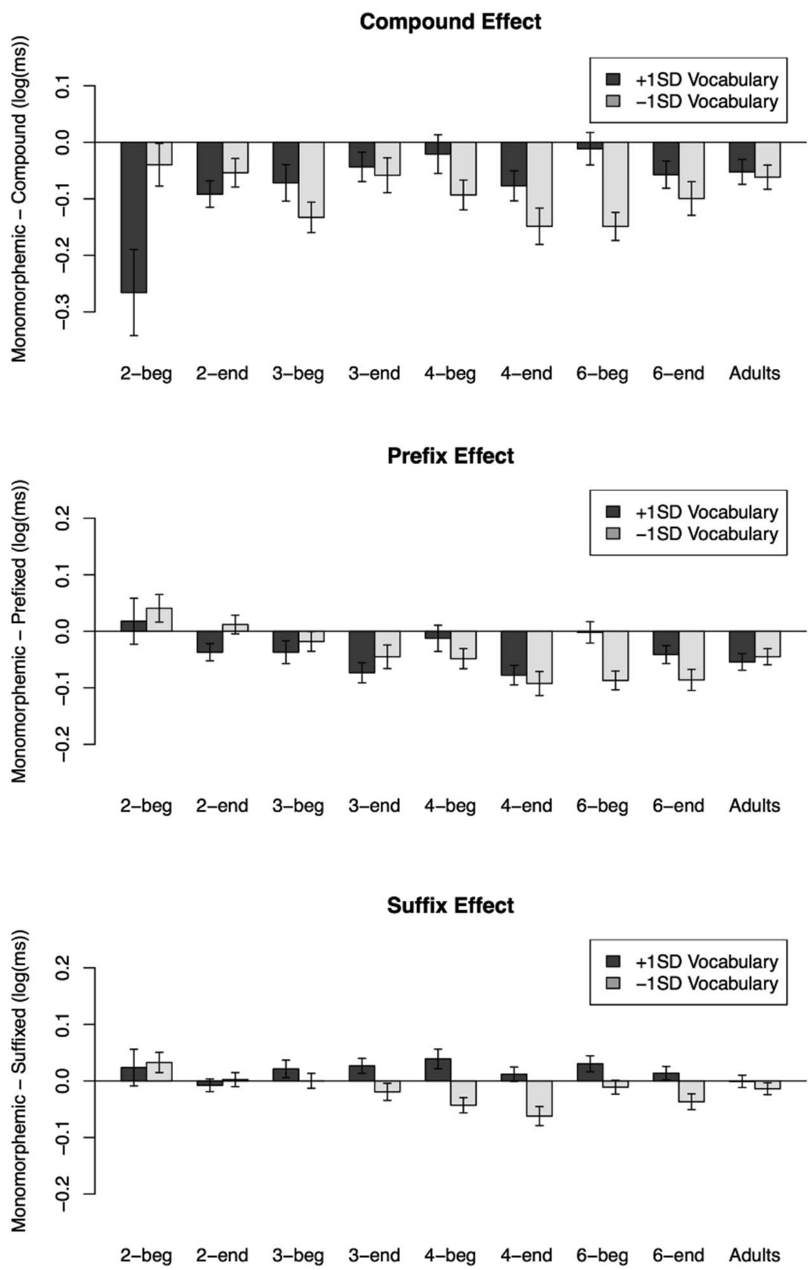

Figure 4. Compound, Prefix, and Suffix Effects for pseudowords in readers with higher (+1 *SD*) and lower (−1 *SD*) vocabulary scores by Age group. Error bars show *SE*s.

order of the emergence of morphological effects in word reading, with compounds being first, followed by suffixes. For pseudowords, the pattern of effects is slightly different. For compounds, a detrimental effect in pseudoword rejection emerges as early as the facilitatory effect in word recognition. The trajectories for suffixes and prefixes in pseudowords differ from those in words: Prefixes have no effect on pseudoword rejection early in development, but hamper it later on, while suffixes have no effect. The lack of morphological effects in pseudoword rejection can be interpreted in two ways: either readers are not affected by morphemes because they are too sophisticated to be misled or because they are too unsophisticated to even notice the morphemes. Because of the simultaneous onset of compound effects in words and pseudowords and because of the developmental progress from no effects toward effects in later grades for prefixed pseudowords, we believe that the latter explanation is more justified and also in line with the interpretation in previous studies (Casalis et al., 2015; Quémart et al., 2012).

The differential patterns for compounds, prefixes and suffixes can be best explained by a preference for stems as reading units and a left-to-right bias that favors suffixes over prefixes, as suggested by Cutler et al. (1985). The relatively early emerging and stable compound effect indicates that stems are clearly the most relevant units in word recognition. Considering that stems are the most informative parts of words, focusing on them is a sensible strategy both when extracting meaning in natural reading and for deciding on lexical status in lexical decision (see also Bertram & Hyönä, 2003). The observed relevance of the stem converges with evidence from masked priming, indicating that children show sensitivity to stems even in the absence of suffixes at sublexical stages of word processing (Beyersmann, Grainer, et al., 2015). The importance of stems can also contribute to explaining the differential processing of prefixes and suffixes. Because of the salient left-most position of the stem in suffixed words, the representation of the stem can be activated relatively quickly, allowing fast verification of its lexicality. Activation of the whole suffixed form itself, as well as coactivation of the affix and forms sharing the same stem and/or the same suffix additionally boosts word recognition (Reichle & Perfetti, 2003; Schreuder & Baayen, 1995). As Cutler et al. (1985) propose, prefixed words carry less information about lexicality and content in the salient left-most position than equivalent suffixed words. The early activation of a prefix in the salient position might therefore not bolster word recognition much and additional activation of the stem in the less salient position or from the whole prefixed word is necessary to decide on the words' lexicality. However, in the case of pseudowords, the early activation of a salient prefix leads to a prolonged "search" in attempt to activate a matching whole-word representation. When this remains unsuccessful, it results in the observed disadvantage for prefixes in pseudoword rejection. The salient position of the stem also explains the diminished role of suffixes in pseudoword rejection: the pseudostem in the salient first position allows fast lexical decision based on the stem. When neither a whole suffixed form, nor a stem, nor a related form sharing the stem can be activated, evidence against word status accumulates fast despite the existing suffix, and the suffixed pseudoword can be rejected relatively quickly with high certainty. The explanation presented here for the differential effects for prefixed and suffixed derivations assumes that prefix and suffix processing reflects the same locus. Alternative explanations are possible that locate prefixes and suffixes at different stages in the reading system. Beyersmann, Grainer, et al. (2015) discuss the possibility that suffixes are represented sublexically, but prefixes only supralexically. This would indicate that prefixed words are not decomposed until they have been accessed as wholes. Prefix and suffix processing could thus involve fundamentally different processes. Clearly, further research is required to answer this question.

The observed pattern of effects has important consequences for the multiple-route model (Grainger & Ziegler, 2011), which is currently the only model that makes explicit assumptions about the mechanisms of morphological processing from a developmental perspective. It includes the development of an access mechanism via sublexical morphological decomposition in the so-called fine-grained route. This route is thought to involve the establishment and use of orthographic representations of affixes through letter chunking. Consequently, the shift from sequential letter-by-letter decoding to the fine-grained route, which might also allow more parallel processing, is hypothesized to entail an increased sensitivity to morphological structure. This expectation converges with our empirical results. However, the fine-grained route in the multiple-route framework is centered on small, reoccurring letter chunks, which is affixes, and is hypothesized to work in a parallel fashion. Such a decomposition mechanism would predict the emergence of suffix and prefix effects at the same early time in development and compound effects later on. Our study showed the opposite pattern with compound effects developing in the earliest stages, followed by suffix and prefix effects. In the light of our results, a left-to-right parsing mechanism in children, tuned to extract stems, seems more likely than a parallel affix-stripping mechanism. It is possible to attribute the activation of stems to the coarse-grained route, as Beyersmann, Grainger, et al. (2015) suggests, but such an interpretation is problematic in our case as the coarse-grained route is even more parallel in nature, which (a) is not compatible with morphological type differences, and (b) demands higher expertise in mapping letters to word representations. Therefore, we suggest that developmental models of visual word recognition not only need to incorporate affixes as important functional units, but also need to account for the early role of stems. Moreover, the parallel nature versus left-to-right bias of processing in the fine-grained route needs to be reconsidered to account for the distinct developmental trajectories of different morphological types.

Furthermore, the second main finding of our study shows that the trajectories of morphological processing are moderated by interindividual differences in vocabulary knowledge. For words, readers with higher vocabulary show effects from all morphological types already in 2nd grade, and thus earlier than readers with lower vocabulary. This can very well be accounted for by the degree to which children were able to set up morphemes as access units as a function of their experience with morphologically complex forms and with single constituent morphemes, as Schreuder and Baayen (1995) imply. Good representations of the whole-word form itself, as well as the constituent morphemes and their related forms bolsters recognition at the access level (Schreuder & Baayen, 1995). This happens more when more extensive and consistent vocabulary knowledge is available (Goodwin et al., 2014; Reichle & Perfetti, 2003). Higher vocabulary readers thus show benefits from compounds, prefixed and suffixed words relative to monomorphemic words already early from 2nd grade. For lower vocabulary readers morphology is more demanding. Compounds showed no effect, suffixes had a detrimental effect early in development and prefixes throughout development. This means that for lower vocabulary participants, stems are apparently not able to boost activation in word recognition. When less vocabulary is available to detect the form-meaning regularities, the ability to activate the stem might take longer to be learned. As a result, activation takes longer or is weaker because of the limited vocabulary knowledge and does not profit from as many coactivated forms that could boost word recognition. The special difficulty of prefixed words is probably due to the second position of the stem, which is a further disadvantage, as discussed above, that is especially detrimental when scant vocabulary knowledge is available.

Vocabulary knowledge similarly moderates morphological effects in pseudoword rejection. Pseudocompounds and prefixed pseudowords are harder to reject for readers with high vocabulary already in 2nd grade. An interesting find was that suffixes do even have a facilitatory effect on pseudoword rejection for high vocabulary readers in Grades 3 and 4. Possibly, having many stable representations of words can also support the rejection of pseudostems, when the stem is in the most salient position. The pseudoword can then be rejected on the basis of the nonexistent stem and activation of the existing suffix is less disruptive for high vocabulary readers. Burani et al. (2002) also suggested that suffixes in pseudowords might be used solely as decoding chunks, thus saving decoding time, while the lexical decision is still based on the stem. For lower vocabulary readers, pseudocompounds and prefixes also hinder rejection, albeit later than for their higher vocabulary peers, namely from around 3rd grade. Moreover, lower vocabulary readers show a detrimental effect also from suffixes in pseudowords in Grade 4 and 6. Because of the smaller vocabulary, it may take longer for them to establish stable access representations of morphemes that produce activation interfering with rejection of complex pseudowords. It is noteworthy that the prefix effect for pseudowords and for words goes in the same direction in lower vocabulary readers, which is also the direction of the pseudoword effect in higher vocabulary readers. Moreover, the suffix effect for pseudowords in Grade 4 and 6 lower vocabulary readers resembles their suffix effect for words in Grades 2 and 3. Thus, lower vocabulary readers seem to process words the same way as pseudowords in the early elementary school years. We suggest that this is the case, because many morphemes are unknown to them and they were not (yet) able to develop access representations for many morphemes as a result of their smaller vocabulary knowledge. Consequently, our findings on the influence of vocabulary knowledge strongly imply that interindividual differences need to be considered as relevant factors in the development of morphological decomposition.

Some limitations of the present study need to be resolved to meaningfully integrate the above named aspects into models of reading development or even propose specific developmental models of complex word recognition. The first concerns the nature of affixes as functional units in reading: it is unclear whether they are merely cues for lexical status and/or increase word-likeness or are actually functional reading units. The differential effects and developmental trajectories of prefixed and suffixed words and pseudowords in our study suggest that affix activation might be an integral part of lexical access, going beyond signaling lexical status or increasing word-likeness. Investigations targeted especially at the processing differences and commonalities of prefixed and suffixed words can shed more light on this issue. Equally, another issue to be examined in this context is the role of stem activation, for which evidence has accumulated recently, not only through the present study, but also in studies using other methods, such as masked priming (Beyersmann, Grainger, et al., 2015). To better understand the dominant role of stems in word recognition, intensive investigation of compound processing in early reading acquisition seems particularly promising. Especially in German, compounding is extremely productive and compounds can be created and interpreted spontaneously. Children encounter many compounds early in reading development and even texts for beginning readers usually encompass compounds (Segbers & Schroeder, in press). Consequently, the recognition of stems is particularly useful in that language. Thus, cross-linguistic studies on the role of stems are very valuable, particularly comparing compound recognition in languages with less productive compounding. Another issue to be examined bears on the relationship between vocabulary knowledge and morpheme use in reading. In the present study, we focused on the impact of vocabulary knowledge on morpheme use. However, it might not be a causal relationship in one direction, such that higher vocabulary increases the use of morphology. It is also possible that those children who are more expert in decomposing words into their morphemes are able to use this competence to grow their vocabulary knowledge. This is also of particular interest for educational practice and reading interventions.

To sum up, the present study extended evidence on the importance of morphemes in reading development to German. It furthermore extended the age range for which the phenomenon is studied, systematically delineating the trajectory of the development of morphological reading and revealing that effects of compound structure already arise at the very beginning of elementary school in Grade 2, followed later by suffix and prefix effects. In addition, the intriguing differences in the development and processing of compounds, prefixed and suffixed words and pseudowords highlight the importance of stem and affix recognition rather than affix-stripping. The development and use of stems and affixes as access units in the recognition of complex words depends on experience with whole-word forms and single constituent morphemes. Finally, our results reveal the crucial relationship between vocabulary knowledge and morpheme use. For the decomposition of complex words, children need stable morpheme representations that allow fast activations, especially of stems to bolster word recognition. The present study thus provides novel comprehensive insights into morphemes as units in reading development and consequences for the advancement of theories of developmental models of word recognition explicitly accounting for emerging mechanisms of morphological processing.

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Appendix

Results From Post-Hoc Comparisons of Age Groups and Morphological Types

Table A1

Exact t- and p-Values for Each Post Hoc Age Group and Morphological Type Comparison for Words Using Cell Means Coding and Single df Contrasts

	Grade 2		Grade 3		Grade 4		Grade 6		
Effects	Beg	End	Beg	End	Beg	End	Beg	End	Adults
					Response times				
Compound effect	$t = -.44$, $p = .66$	$t = 3.30$, $p < .001$	$t = 3.30$, $p < .001$	$t = 2.74$, $p = .006$	$t = 4.80$, $p < .001$	$t = 3.98$, $p < .001$	$t = 3.40$, $p < .001$	$t = 3.13$, $p = .002$	$t = 2.17$, $p = .03$
Prefix effect	$t = -.63$, $p = .53$	$t = .90$, $p = .36$	$t = -.02$, $p = .98$	$t = .84$, $p = .40$	$t = 1.10$, $p = .26$	$t = 2.52$, $p = .01$	$t = 2.90$, $p = .004$	$t = 2.00$, $p = .04$	$t = 2.76$, $p = .006$
Suffix effect	$t = -.74$, $p = .46$	$t = .78$, $p = .44$	$t = 1.23$, $p = .22$	$t = 2.35$, $p = .02$	$t = 2.09$, $p = .04$	$t = 2.86$, $p = .004$	$t = 3.51$, $p < .001$	$t = 2.51$, $p = .01$	$t = 2.09$, $p = .04$
					+1 *SD* Vocabulary Knowledge				
Compound effect	$t = 1.10$, $p = .24$	$t = 4.34$, $p < .001$	$t = 5.59$, $p < .001$	$t = 4.37$, $p < .001$	$t = 7.79$, $p < .001$	$t = 4.22$, $p < .001$	$t = 4.85$, $p < .001$	$t = 3.34$, $p < .001$	$t = 2.73$, $p = .006$
Prefix effect	$t = 1.32$, $p = .19$	$t = 2.29$, $p = .02$	$t = 4.68$, $p < .001$	$t = 3.30$, $p < .001$	$t = 3.08$, $p = 002$	$t = 2.63$, $p = .009$	$t = 2.56$, $p < .009$	$t = 1.52$, $p = .13$	$t = 2.03$, $p = .04$
Suffix effect	$t = -.15$, $p = .88$	$t = 2.85$, $p = .004$	$t = 5.32$, $p < .001$	$t = 3.72$, $p < .001$	$t = 3.46$, $p < .001$	$t = 2.68$, $p = .007$	$t = 4.20$, $p < .001$	$t = 2.94$, $p = .003$	$t = 2.08$, $p = .04$
					−1 *SD* Vocabulary Knowledge				
Compound effect	$t = -1.15$, $p = .25$	$t = 1.10$, $p = .27$	$t = .91$, $p = .36$	$t = -.39$, $p = .69$	$t = 1.42$, $p = .16$	$t = 1.92$, $p = .05$	$t = 1.47$, $p = .14$	$t = 1.81$, $p = .07$	$t = 1.25$, $p = .21$
Prefix effect	$t = -3.08$, $p = .002$	$t = -2.59$, $p = .009$	$t = -2.53$, $p = .01$	$t = -1.28$, $p = .20$	$t = -2.06$, $p = .04$	$t = -1.22$, $p = .22$	$t = -2.09$, $p = .04$	$t = -.71$, $p = .48$	$t = 3.21$, $p = .001$
Suffix effect	$t = .76$, $p = .45$	$t = -2.38$, $p = .02$	$t = -2.09$, $p = .04$	$t = -.47$, $p = .64$	$t = .63$, $p = .53$	$t = 1.74$, $p = .08$	$t = 1.92$, $p = .05$	$t = .92$, $p = .36$	$t = 1.61$, $p = .11$
					Error rates				
Compound effect	$t = -.63$, $p = .53$	$t = 3.05$, $p = .02$,	$t = 2.28$, $p = .02$	$t = 3.45$, $p < .001$	$t = 2.88$, $p = .004$	$t = 3.66$, $p < .001$	$t = 3.06$, $p = .002$	$t = 3.21$, $p = .001$	$t = 3.36$, $p < .001$
Prefix effect	$t = 1.20$, $p = .23$	$t = .76$, $p = .45$,	$t = 1.84$, $p = .07$	$t = 2.14$, $p = .03$	$t = 1.80$, $p = .07$	$t = 2.87$, $p = .004$	$t = 3.25$, $p = .001$	$t = 3.51$, $p < .001$	$t = 4.38$, $p < .001$
Suffix effect	$t = .19$, $p = .85$	$t = .76$, $p = .45$	$t = -.08$, $p = .93$	$t = 1.27$, $p = .21$	$t = 1.98$, $p = .04$	$t = 1.64$, $p = .10$	$t = 1.08$, $p = .28$	$t = 2.43$, $p < .02$	$t = 3.18$, $p = .001$

(*Appendix continues*)

Table A2
Exact t- and p-Values for Each Post Hoc Age Group and Morphological Type Comparison for Pseudowords Using Cell Means Coding and Single df Contrasts

	Grade 2		Grade 3		Grade 4		Grade 6		
Effects	Beg	End	Beg	End	Beg	End	Beg	End	Adults
					Response times				
Compound effect	$t = -2.06, p = .04$	$t = -3.70, p < .001$	$t = -4.77, p < .001$	$t = -2.11, p = .03$	$t = -2.94, p = .003$	$t = -4.63, p < .001$	$t = -4.39, p < .001$	$t = -3.48, p < .001$	$t = -3.09, p = .002$
Prefix effect	$t = 1.59, p = .11$	$t = -1.32, p = .19$	$t = -1.37, p = .17$	$t = -3.98, p < .001$	$t = -2.33, p = .03$	$t = -5.46, p < .001$	$t = -3.65, p < .001$	$t = -4.12, p < .001$	$t = -3.93, p < .001$
Suffix effect	$t = 1.84, p = .07$	$t = -.37, p = .71$	$t = .9, p = .37$	$t = .70, p = .48$	$t = -1.30, p = .20$	$t = -1.16, p = .25$	$t = .55, p = .58$	$t = -.57, p = .57$	$t = -.86, p = .39$
					1 *SD* Vocabulary Knowledge				
Compound effect	$t = -3.49, p < .001$	$t = -3.93, p < .001$	$t = -2.23, p = .03$	$t = -1.67, p = .09$	$t = -.61, p = .54$	$t = -2.91, p = .004$	$t = .40, p = .69$	$t = -2.39, p = .02$	$t = -2.38, p = .02$
Prefix effect	$t = .44, p = .66$	$t = -2.44, p = .01$	$t = -1.83, p = .07$	$t = -4.11, p < .001$	$t = -.54, p = .59$	$t = -4.51, p < .001$	$t = .10, p = .92$	$t = -2.59, p = .01$	$t = -3.69, p < .001$
Suffix effect	$t = .73, p = .47$	$t = .69, p = .49$	$t = 1.36, p = .17$	$t = 2.01, p = .04$	$t = 2.25, p = .02$	$t = .94, p = .35$	$t = 2.15, p = .03$	$t = 1.16, p = .25$	$t = -.08, p = .94$
					−1 *SD* Vocabulary Knowledge				
Compound effect	$t = -1.05, p = .29$	$t = -2.14, p = .03$	$t = -4.95, p < .001$	$t = -1.89, p = .07$	$t = -3.53, p < .001$	$t = -4.62, p < .001$	$t = -5.98, p < .001$	$t = -3.35, p < .001$	$t = -2.90, p = .004$
Prefix effect	$t = 1.67, p = .09$	$t = .72, p = .47$	$t = -1.03, p = .30$	$t = -2.16, p = .03$	$t = -2.74, p = .006$	$t = -4.33, p < .001$	$t = -5.23, p < .001$	$t = -4.60, p < .001$	$t = -3.18, p = .001$
Suffix effect	$t = 1.83, p = .07$	$t = .19, p = .85$	$t = .02, p = .99$	$t = -1.28, p = .20$	$t = -3.20, p = .001$	$t = -3.69, p < .001$	$t = .91, p = .36$	$t = -2.64, p = .008$	$t = -1.33, p = .19$
					Error rates				
Compound effect					$t = -5.70, p < .001$				
Prefix effect					$t = -2.00, p = .04$				
Suffix effect					$t = 1.80, p = .07$				

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