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Embedded stems as a bootstrapping mechanism for morphological parsing during reading development

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ABSTRACT

The aim of the current research was to test the hypothesis that the activation of embedded words (e.g., the *farm* in *farmhouse*) is the starting point for the development of an abstract morphological parsing system in children's reading. To test this hypothesis, we examined the developmental trajectory of compound priming effects in third- and fifth-grade primary school children, high school students, and adults. Both children and adults participated in a masked priming lexical decision study comparing transparent compound (*farmhouse–farm*), opaque compound (*butterfly–butter*), and noncompound (*sandwich–sand*) word priming effects measured relative to an unrelated control. The results showed significant and equal priming effects in the two compound conditions but not in the noncompound priming condition. This robust pattern was clearly and unequivocally observed across all groups of participants. Our data suggest that even the youngest readers have already acquired the ability to rapidly and automatically identify embedded stems and are sensitive to the overall structure of compound words (full decomposition). We conclude that the activation of embedded stems provides a critical starting point in children's use of morphological information when learning to read.

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Introduction

How do children learn to read a word like *pack*? Decades of research tell us that key to this process is children's ability to sound out, or phonologically decode, the word using their knowledge about the mappings between letters and sounds (National Reading Panel, 2000). However, what happens when children then see complex words such as *un-pack, pack-ing,* and *back-pack*? These words all are linked to *pack* by their meaning, and indeed all contain the word *pack* within them, but phonological decoding alone does not capture any of this information. To become proficient readers, children need to learn much more than just how to sound words out; they must also acquire and draw on a wealth of knowledge about the basic meaning units represented within words, or their morphology. Indeed, more than 80% of words in the English language are morphologically complex (Baayen, Piepenbrock, & van Rijn, 1993); that is, they comprise multiple morphemes such as a stem (*pack*) plus an affix (*un* + *pack* or *pack* + *ing*) or two concatenated stems (*back* + *pack*). Affixes like *un* can be added to hundreds of words (e.g., *un-zip, un-fold, un-wrap*), and they can be used to make up new words on the spot (e.g., *un-work, un-sleep*). Once children have acquired knowledge about morphological regularities, they no longer need to rely on mapping new written words onto their meanings on an item-by-item basis because they can begin to derive word meaning on the basis of the meaning of the word's constituent morphemes. The systematicity of morphological relationships between words, thus, has strong potential to be drawn on to support children's reading development (Castles, Rastle, & Nation, 2018; Rastle, 2018), and the question of how and when morphology should be taught at schools has been hotly debated during recent years (Bowers & Bowers, 2018; Rastle & Taylor, 2018; Taylor, Davis, & Rastle, 2017).

Adults are experts at rapidly decomposing printed words such as *farmer* into *farm* + *er.* In fact, their ability to decompose words is automatized to the point where it "blindly" applies to any word that carries an affix such as the "pseudo-complex" word *corner* decomposed into *corn* + *er,* although *corn* is semantically unrelated to *corner.* Much evidence for this automatic decomposition process comes from research using masked priming (for reviews, see Amenta & Crepaldi, 2012; Rastle & Davis, 2008). This research has shown that primes like *farmer* and *corner* facilitate responses to the embedded target (FARM/CORN) relative to an unrelated control (e.g., *hunter–FARM/hunter–CORN*). Crucially, priming does not arise with words like *cashew,* consisting of an embedded word *cash* followed by a nonmorphemic ending *ew* (e.g., Beyersmann, Ziegler, et al., 2016; Fiorentino & Fund-Reznicek, 2009; Rastle, Davis, & New, 2004), suggesting that facilitation occurs only in the presence of an affix. This points to the affix as playing a key role in the processing of complex words by adult readers.

Whereas the rapid and automatic activation of affixes clearly forms a core aspect of the skilled reading system, it is less clear how and when children begin to acquire this important process. Several studies have demonstrated children's early explicit knowledge of morphological structures (Bertram, Laine, & Virkkala, 2000; Carlisle & Katz, 2006; Deacon & Bryant, 2006a, 2006b; Kemp & Bryant, 2003; Pacton et al., 2018; Pacton, Foulin, Casalis, & Treiman, 2013; Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009). Further evidence for the important role of morphological knowledge in reading development comes from studies using lexical decision tasks (Burani, Marcolini, & Stella, 2002; Casalis, Quemart, & Duncan, 2015; Dawson, Rastle, & Ricketts, 2018; Hasenäcker, Schroeter, & Schroeder, 2017; Perdijk, Schreuder, Baayen, & Verhoeven, 2012). For instance, Dawson et al. (2018) compared performance to pseudomorphemic nonwords formed of a stem and a suffix (e.g., *earist*) and nonmorphemic nonwords formed of a stem and a nonmorphological ending (e.g., *earilt*) and found that the pseudomorphemic nonwords took longer to reject in the older participants they tested (adults and adolescents) but not in the younger participants (7- to 9-year-olds). The younger children did, however, produce more errors to the pseudomorphemic nonwords, suggesting that beginning readers exhibit some sensitivity to pseudo-morphological structure (for converging evidence, see also Beyersmann, Grainger, Casalis, & Ziegler, 2015). Although it is clear from these findings that morphological structure can influence word recognition in readers as young as 7 years, it does not determine the automaticity with which morphological knowledge affects children's reading.

Indeed, the acquisition of more automatized morphological processing mechanisms for reading appears to take a relatively long time (for a recent review, see Rastle, 2018). Particularly informative in this regard have been studies that applied the masked priming paradigm (which, as we described earlier, has been widely used in adults) to study the development of morphological reading skill in children, thereby providing a unique window into the intersection between skilled and developing reading. The key finding, with respect to the current study, is the combination of significant masked priming from transparent derived word primes (e.g., *farmer–farm*) and the absence of effects with opaque derived word primes (e.g., *corner–corn*), as reported in studies testing English- and Hebrew-speaking beginning readers (Beyersmann, Castles, & Coltheart, 2012; Schiff, Raveh, & Fighel, 2012). The absence of priming in children as advanced as Grade 5 suggests that the acquisition of a fully automatized semantically blind morphological decomposition mechanism is a quite late acquired milestone in children's reading acquisition (Beyersmann, Castles, et al., 2012; but see Quémart, Casalis, & Colé, 2011, for conflicting evidence from French). Indeed, it might not emerge until children reach high school (Dawson et al., 2018; Schiff et al., 2012).

Grainger and Beyersmann (2017) explained this pattern of effects by a combination of beginning readers' sensitivity to morpho-semantics (i.e., knowing that *farm* and *farmer* are related) acquired via exposure to spoken language prior to learning to read plus a dominance of word-based processing as opposed to morpheme-based processing during the initial phases of learning to read. The hypothesized dominance of word-based processing gives rise to the central notion of stem precedence[1] in Grainger and Beyersmann's proposal. Stem precedence arises from the application of a non-morphological process of embedded word activation. Embedded words are thought to be automatically activated during reading (e.g., Beyersmann, Casalis, Ziegler, & Grainger, 2015; Beyersmann, Cavalli, Casalis, & Colé, 2016; Snell, Grainger, & Declerck, 2018), with the length of the embedded word determining the amount of activation and with edge-aligned embedded words (i.e., those that are aligned with either the first or last letter of the embedding word such as *corn* in *corner* and *late* in *relate*) also benefitting from the greater visibility of outer letters (Grainger, Dufau, & Ziegler, 2016). Embedded stems will typically be the longest edge-aligned embedded word and, therefore, will dominate processing along with the representation of the whole word. For example, on presentation of the word *corner,* the representations of the whole word *corner* and the edge-aligned embedded word *corn* will receive the most activation. Furthermore, in the case of semantically transparent derivations (e.g., *farmer*), the morpho-semantic compatibility of the embedded stem (*farm*) with the embedding complex word (*farmer*) reinforces the coactivation of the derived word and the stem. The absence of priming with opaque words in beginning readers is then explained by the lateral inhibition that is hypothesized to operate between coactivated but incompatible whole-word orthographic representations such as *corner* and *corn* and *cashew* and *cash.* It is the relatively late acquisition of affix representations that is thought to drive the opaque priming effects seen in older children and adults via the principle of full decomposition. That is, the fact that the embedding word (e.g., *corner*) can be exhaustively decomposed into a set of component morphemes (*corn* + *er*) helps to maintain activation of the embedded word (*corn*) in spite of lateral inhibition (see Grainger & Beyersmann, 2017, for more details).

In line with this theorizing, the emergence of robust embedded word priming effects during the early years of primary school suggests that children are indeed proficient at automatically activating embedded words (e.g., Beyersmann, Grainger, et al., 2015; Hasenäcker, Beyersmann, & Schroeder, 2016; for converging evidence, see also Nation & Cocksey, 2009). Once children become proficient at identifying embedded words, they would then be able to use the activation of embedded words as a bootstrapping mechanism for initiating an automatic morphological decomposition process. The ability to activate embedded words would equip children with a powerful tool at the beginning stages of their reading development to not only identify familiar words but also recognize unfamiliar words that contain the known embedded word units within them. This ability to derive meanings from unfamiliar words would lead to a rapid expansion of children's vocabulary, which would initially be particularly successful in their attempt to derive meanings from compound words that can be exhaustively decomposed into familiar subunits. For instance, knowing the meaning of *farm* (a place where we raise animals and grow crops) and the meaning of *house* (a building in which we

[1] We note, however, that one could also argue for affix precedence rather than stem precedence given that affixes constitute short high-frequency constituents of words. The counterargument here lies in the key role for between-word spaces in guiding orthographic learning. Free-standing stems are first learned as words surrounded by spaces before being processed as edge-aligned embedded words. This generates the interesting hypothesis that languages that use an alphabetic script without between-word spacing (e.g., Thai) might, on the contrary, show affix precedence rather than stem precedence during reading development.

sleep and eat) would allow children to derive the meaning of *farmhouse* (a building on the farm in which the farmer and the farmer's family sleep and eat) without ever having previously acquired this compound word. We hypothesize that this ability to decompose compound words such as *farmhouse* should quickly emerge during the early stages of children's reading acquisition. The results of Hasenäcker et al. (2017) provide some initial support for this hypothesis. These authors analyzed the lexical decision data obtained from a large sample of German elementary school children tested with a large sample of words and found that the effects of compound status compared with monomorphemic words had already emerged in Grade 2. Furthermore, in line with the hypothesized later development of affix representations, the effects of derived word status were found to emerge later in these authors' study.

The goal of our study was to provide a further test of this hypothesis by comparing masked priming effects of transparent compound words (*farmhouse–farm*), opaque compound words (*butterfly–butter*), and noncompound words (*sandwich–sand*) in four different participant groups (third graders, fifth graders, high school students [high schoolers], and adults). From previous research, we know that skilled readers show significant priming in the transparent and opaque compound conditions but not in the noncompound condition (Fiorentino & Fund-Reznicek, 2009). Thus, these results are similar to the automatic segmentation effects observed in affixed words (e.g., Beyersmann, Ziegler, et al., 2016; Rastle et al., 2004), suggesting that adults automatically activate the embedded word constituents whenever the prime can be exhaustively decomposed into morphemic subunits, and therefore comply with the principle of full decomposition. The goal of the current study was to extend this paradigm to three different groups of developing readers to test when children first begin to show evidence for automatic segmentation of compound words. If it is indeed the case that embedded words are used as a bootstrapping mechanism to initiate affix stripping in children's reading development (Grainger & Beyersmann, 2017), children should quickly become proficient at automatically activating the orthographic representations of edge-aligned embedded words when these provide a complete description of the embedding stimulus (e.g., *butter* and *fly* in *butterfly*) and independent of the semantic relation between these words. That is, we would predict robust and comparable transparent and opaque compound priming effects across all participant groups relative to the noncompound control.

In addition to the masked primed lexical decision task, each participant was assessed with vocabulary, reading proficiency, and morphological awareness tests. These measures were used to control for individual differences in language proficiency and were included as covariates in the analyses outlined below.

Method

Participants

Three groups of children (third graders, fifth graders, and high schoolers) and one group of adults participated in this study. The group of adults consisted of 48 students from Macquarie University, all English native speakers, who participated for course credit. In addition, 33 third graders (12 female and 21 male; mean age = 9:11 [years: months], range = 9:5–10:7), 46 fifth graders (29 female and 17 male; mean age = 11:10, range = 10:7–12:6), and 35 high schoolers (sixth to twelfth graders; 12 female and 23 male; mean age = 14:5, range = 12:3–18:6), all English native speakers, participated in this study. All children from two Grade 3 and two Grade 5 classes were invited to participate, but only those who returned consent forms were included. The high-school students were recruited via the Neuronauts Brain Science Club of the ARC Centre of Excellence in Cognition and its Disorders and included depending on individual interest. On completion of the study, third and fifth graders received a small gift, whereas high schoolers received monetary reimbursement of AU $20 each.

Materials

We selected 32 transparent compound words (*snowball*), 32 opaque compound words (*butterfly*), and 32 noncompound words (*sandwich*) from the CELEX lexical database (Baayen et al., 1993), which were used as primes in the masked priming study (Appendix A). Similar to previous derived word priming studies (e.g., Rastle et al., 2004) in which the target was typically embedded in the word-initial position (*farmer–FARM, corner–CORN, cashew–CASH*), target words were always embedded in the word-initial position (*snowball–SNOW, butterfly–BUTTER, sandwich–SAND*). Transparent compound words were chosen, such that the meaning of the whole word could be derived from the meaning of its two constituents (*snowball = ball of snow, moonlight = the moon's light*). Opaque compound words were semantically unrelated to the first constituent (*butterfly–BUTTER*; i.e., we excluded prime–target pairs such as *friendship–FRIEND, brainstorm–BRAIN,* and *stagehand–STAGE*). Noncompound words included an embedded word at the beginning of the letter string (*must* in *mustard, sand* in *sandwich*), but the rest of the letter string did not form an existing word (*ard* and *wich* are not words).

For each related prime, we selected a semantically, morphologically, and orthographically unrelated control prime (*pumpkin–PUMP* vs. *barrier–PUMP*) that was identical in length. Within each condition, 50% of the unrelated primes were morphologically complex and 50% were monomorphemic. Although our participants were unlikely to develop a response strategy in this task (because primes were entirely masked), we balanced the number of poly- and monomorphemic primes in the unrelated condition to further rule out any strategic biases in this task. Examples for stimuli in each condition are provided in Table 1.

Word properties were retrieved from the Children's Printed Word Database (Masterson, Stuart, Dixon, & Lovejoy, 2010) and are listed in Table 2. Target and prime words in the three morphological conditions were matched on orthographic neighborhood, phonological neighborhood, word frequency, number of letters, number of phonemes, and number of syllables (Table 2). Semantic relatedness values between whole words and their embedded words were extracted using the latent semantic analysis (LSA) web facility (http://lsa.colorado.edu; Landauer & Dumais, 1997) and are also reported in Table 2.

Nonword targets were created for the purpose of the lexical decision task by changing one letter in a real word (*bath–bith*). Each nonword was preceded by either a related or an unrelated word prime (*bathrobe–BITH* vs. *armchair–BITH*). Half of the primes were morphologically complex and half were monomorphemic. Word and nonword targets were matched on length. To avoid target repetition, we created two counterbalanced lists.

Procedure

Stimuli were presented in the center of an LCD computer screen using DMDX software (Forster & Forster, 2003). Each trial consisted of a 500-ms forward mask of hash keys, then a 50-ms prime in lowercase, and then the uppercase target. The target remained present until the response was made or until 3 s had elapsed. Participants were instructed to respond as quickly and accurately as possible.

Measures of individual differences

Vocabulary

The Wechsler Adult Intelligence Scale–Third Edition (WAIS-III) Vocabulary subtest was administered to obtain an estimate of general level of lexical knowledge (Wechsler, 1997). Participants were presented with individual words (*lamp*) and asked to provide definitions ("a source of light"). The score was calculated based on the WAIS-III scoring system.

Reading proficiency

Reading proficiency was assessed using the Sight Word Efficiency subtest and Phonemic Decoding subtest of the Test of Word Reading Efficiency, Form A (TOWRE; Torgesen, Wagner, & Rashotte, 1999).

Table 1
Examples for prime–target pairs across conditions.

	Related	Unrelated
Transparent	snowball–SNOW	passport–SNOW
Opaque	butterfly–BUTTER	household–BUTTER
Form	sandwich–SAND	vampire–SAND

Table 2
Descriptive statistics for target words and prime words extracted from the Children's Printed Word Database.

	Transparent compound condition	Opaque compound condition	Noncompound condition
	Targets		
Logarithmic word frequency	4.6 (1.5)	4.3 (1.4)	3.9 (1.7)
Number of syllables	1.1 (0.2)	1.1 (0.3)	1.0 (0.0)
Number of phonemes	3.1 (0.8)	3.3 (0.8)	3.3 (0.6)
Number of letters	4.1 (0.7)	4.2 (0.8)	3.9 (0.7)
Orthographic neighborhood	5.9 (4.0)	6.0 (4.5)	7.7 (4.7)
Phonological neighborhood	13.4 (8.6)	11.5 (7.3)	14.4 (7.8)
	Primes		
Logarithmic word frequency	2.5 (1.0)	2.4 (1.5)	2.4 (1.2)
Number of syllables	2.1 (0.4)	2.2 (0.4)	2.6 (0.7)
Number of phonemes	6.4 (1.1)	6.7 (1.1)	6.5 (1.5)
Number of letters	8.3 (1.1)	8.4 (1.2)	8.0 (1.2)
Orthographic neighborhood	0.0 (0.0)	0.0 (0.0)	0.1 (0.3)
Phonological neighborhood	0.0 (0.0)	0.0 (0.0)	0.4 (0.7)
	Prime–target pairs		
LSA semantic relatedness	.28 (.17)	.08 (.07)	.08 (.08)

Note. Standard deviations are in parentheses. Semantic relatedness between primes and targets was calculated using the latent semantic analysis (LSA) web facility (Landauer & Dumais, 1997).

Both subtests measured the number of words/nonwords that participants could name in 45 s (for each test), with increasing difficulty as the test progressed. The Sight Word Efficiency subtest was administered first. Both subtests were scored following the protocol outlined by Torgesen et al. (1999).

Morphological awareness

A modified version of the sentence completion task by Carlisle (1988) was used to examine the ability to choose appropriate derivational forms in an oral sentence context (Carlisle, 2000; Roman et al., 2009). The experimenter first read a word and then a sentence with a missing word (e.g., "Perform. Tonight is the last ____."). Participants were then asked to fill the gap with a corresponding correct morphological form of the word presented at the beginning of the task (*performance*). Ten sentences required the selection of a matching morphologically derived word form (see example above), and 10 involved the production of corresponding stem morphemes (e.g., "Discussion. The friends have a lot to ____." [*discuss*]).

Results

Lexical decisions to word targets were analyzed as follows. Incorrect responses were removed from the reaction time (RT) analysis (7.2% of all data). RTs faster than 300 ms were removed (0.2% of the data). Inverse RTs (1/RT) were calculated for each participant to correct for RT distribution skew and were used throughout the analyses (Kliegl, Masson, & Richter, 2010). Mean RTs and error rates for each participant group are presented in Figs. 1 and 2 (also refer to Appendix B, which details the exact RTs and error rates for each condition). Mean test scores for the individual proficiency measures are presented in Table 3.

We used linear mixed-effects modeling to perform the main analyses (Baayen, 2008; Baayen, Davidson, & Bates, 2008). Fixed effects, random effects, and random slopes were included only if they significantly improved the model's fit in a backward stepwise model selection procedure. Following Barr, Levy, Scheepers, and Tily (2013), we included the maximal random effect log likelihood ratio tests structure justified by the design. Models were selected using chi-square with regular maximum likelihood parameter estimation. Fixed effects of interest were the factors item type (transparent, opa-

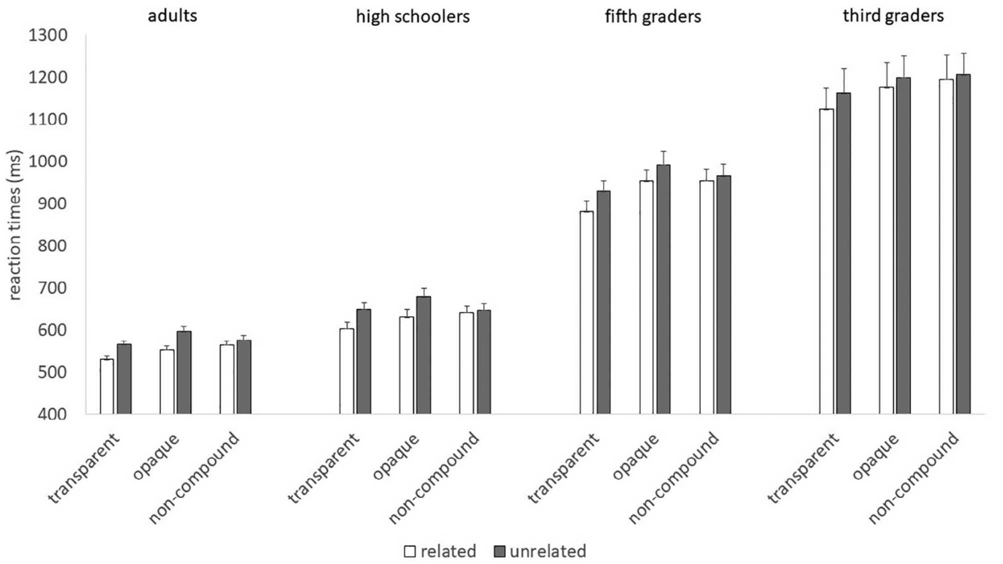

Fig. 1. Mean lexical decision times (ms) and within-participant error bars for each age group.

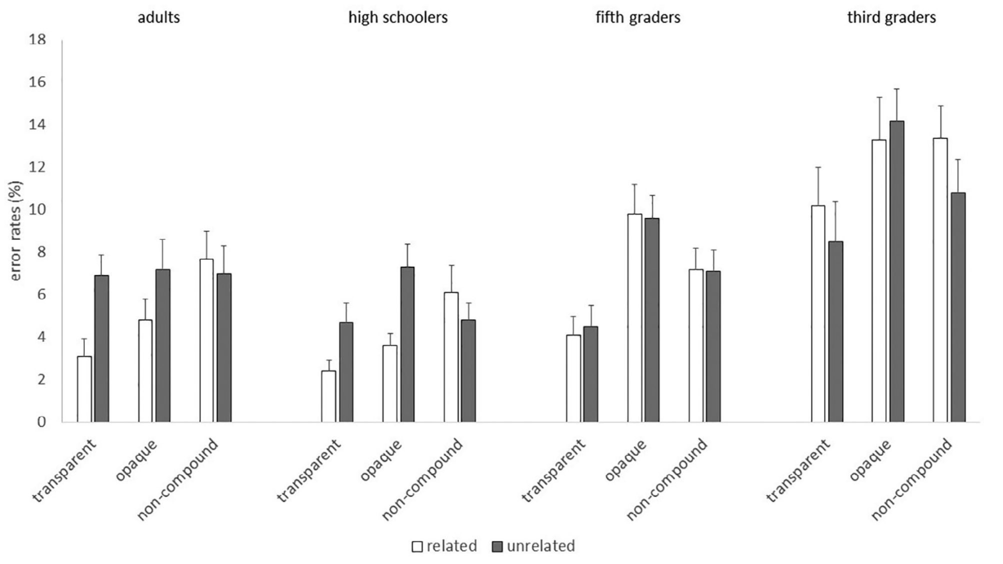

Fig. 2. Mean error rates (%) and within-participant error bars for each age group.

que, or noncompound), relatedness (related or unrelated), group (third graders, fifth graders, high schoolers, or adults), and their interactions. Trial order was included to control for longitudinal task effects such as fatigue and habituation. We also included measures of vocabulary, word reading proficiency, nonword reading proficiency, and morphological awareness as factors to control for individual proficiency differences between participants. Linear mixed-effects models were implemented in the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) in the statistical software R (Version 3.0.3; R Development Core Team, 2008). The final model was refitted after excluding data points

Table 3
Mean test scores averaged across participants for each age group.

Participant group	WAIS-III vocabulary[a]	TOWRE words (max = 108)	TOWRE nonwords (max = 66)	Morphological awareness (max = 20)
Third graders	22.03 (5.41)	59.88 (12.60)	32.55 (12.06)	13.94 (2.87)
Fifth graders	28.83 (4.44)	72.20 (9.97)	38.37 (11.99)	16.74 (1.82)
High schoolers	31.89 (4.01)	88.34 (11.52)	49.20 (11.24)	19.09 (1.29)
Adults	34.44 (5.18)	93.21 (8.98)	60.02 (5.73)	20.00 (0.00)

Note. Standard deviations are in parentheses.
[a] The Wechsler Adult Intelligence Scale–Third Edition (WAIS-III) Vocabulary subtest used different stop rules based on participant age. As a result, the total reachable number of points differed for ages 7–11 years (50 points), ages 12–14 years (56 points), and ages 15 years and over (62 points).

whose standardized residuals were larger than 2.5 in absolute value (see Baayen, 2008), leading to the removal of 1.2% of the total data. All continuous variables were centered. The lmer default coding for treatment contrasts was used (i.e., reference "related" for factor relatedness; reference "noncompound" for factor item type), and factor item type was releveled to "transparent" and "opaque" in order to evaluate the interaction between item type and relatedness. The *p* values were determined using the package lmerTest (Kuznetsova, Brockhoff, & Christensen, 2014).

In the RT analyses, the final model included the factors item type, relatedness, group, word reading proficiency, and trial order, the interaction between item type and relatedness, the interaction between relatedness and group, random intercepts for participants and items, and by-participant random slopes for relatedness and trial order. The item type × relatedness × group interaction was not significant, $\chi^2(6) = 8.97$, $p < .175$, and was excluded from the final model. The results revealed a significant interaction between item type and relatedness, $\chi^2(2) = 33.43$, $p < .001$, showing that priming was greater in the transparent compound condition than in the noncompound condition ($t = 5.15$, $p < .001$), greater in the opaque compound condition than in the noncompound condition ($t = 4.86$, $p < .001$), but comparable in the two compound conditions ($t = 0.25$, $p = .806$)[2] (see Fig. 1). The interaction between relatedness and group was significant, $\chi^2(3) = 34.23$, $p < .001$, showing that the overall priming effects were greater for adults than for third graders ($t = 4.59$, $p < .001$) and fifth graders ($t = 4.64$, $p = .001$), greater for high schoolers than for third graders ($t = 3.46$, $p < .001$) and fifth graders ($t = 3.37$, $p < .001$), but comparable for adults and high schoolers ($t = 0.89$, $p = .373$) and comparable for third and fifth graders ($t = 0.41$, $p = .681$).[3] There were significant main effects of word reading proficiency, $\chi^2(1) = 5.33$, $p = .021$, item type, $\chi^2(2) = 11.28$, $p = .004$, relatedness, $\chi^2(1) = 10.95$, $p < .001$, group, $\chi^2(3) = 507.76$, $p < .001$), and trial order, $\chi^2(1) = 22.58$, $p < .001$.

Although the absence of a three-way item type × relatedness × group interaction indicated that a comparable pattern of priming was observed across age groups, post hoc analyses were conducted to test the significance of priming effects within each age group. The analyses confirmed that within each participant group, priming was greater in the transparent compound condition than in the noncompound condition (third graders: $t = 4.73$, $p < .001$; fifth graders: $t = 4.87$, $p < .001$; high schoolers: $t = 5.07$, $p < .001$; adults: $t = 4.78$, $p < .001$), greater in the opaque compound condition than in the noncompound condition (third graders: $t = 3.83$, $p < .001$; fifth graders: $t = 3.74$, $p < .001$; high schoolers: $t = 3.76$, $p < .001$; adults: $t = 3.80$, $p < .001$), but comparable in the two compound conditions (third graders: $t = 0.87$, $p = .387$; fifth graders: $t = 1.10$, $p = .273$; high schoolers: $t = 1.27$, $p = .205$; adults: $t = 0.94$, $p = .346$).

[2] A reviewer raised the point that semantic influences on morphological processing may be greater in primary school children than in the two older age groups. Indeed, the RT means (Fig. 1) were higher for transparent compound words than for opaque compound words for fifth graders (48 vs. 37 ms) and third graders (39 vs. 24 ms). However, post hoc analyses within the two groups of primary school children (i.e., excluding high schoolers and adults) revealed that priming was greater in the transparent compound condition than in the noncompound condition ($t = 4.77$, $p < .001$), greater in the opaque compound condition than in the noncompound condition ($t = 4.46$, $p < .001$), but comparable in the two compound conditions ($t = 0.28$, $p = .781$), thereby providing no statistical evidence for semantic influences on morphological processing in third and fifth graders.

[3] A small number of prime–target pairs (highlighted by an asterisk in Appendix A) varied in phonological form (e.g., *material–mate*). Therefore, we conducted a post hoc analysis in which we excluded the highlighted item pairs, which did not change the significance or direction of any of the observed effect sizes.

Error analyses followed the same logic as the RT analyses. We applied a binomial variance assumption to the trial-level binary data using the function *glmer* as part of the R package lme4. The results revealed a significant interaction between item type and relatedness, $\chi^2(2) = 11.38$, $p = .003$, showing that priming was greater in the transparent compound condition than in the noncompound condition ($z = 2.86$, $p = .004$), greater in the opaque compound condition than in the noncompound condition ($z = 2.88$, $p = .004$), but comparable in the two compound conditions ($z = 0.23$, $p = .822$). The interaction between relatedness and group was significant, $\chi^2(3) = 12.50$, $p = .006$, showing that the overall priming effects were greater for adults than for third graders ($z = 3.04$, $p = .002$) and fifth graders ($z = 2.31$, $p = .021$), greater for high schoolers than for third graders ($z = 2.41$, $p = .016$), marginally greater for high schoolers than for fifth graders ($z = 1.81$, $p = .071$), comparable for adults and high-schoolers ($z = 0.16$, $p = .870$), and comparable for third and fifth graders ($z = 0.70$, $p = .483$).

The interaction between item type and group was also significant, $\chi^2(6) = 17.47$, $p = .008$, showing that, compared with adults, third and fifth graders overall made more errors in responding to target words in the opaque compound condition than in the transparent compound condition ($z = 2.08$, $p = .037$ and $z = 3.38$, $p < .001$) and made more errors in responding to target words in the opaque compound condition than in the noncompound condition ($z = 2.48$, $p = .013$ and $z = 3.28$, $p = .001$).[4] There were also significant main effects of item type, $\chi^2(2) = 10.45$, $p = .005$, and group, $\chi^2(3) = 22.37$, $p = .005$. No other effects were significant.

Despite the absence of a three-way item type × relatedness × group interaction, post hoc analyses were carried out to examine priming effects within each individual participant group. The breakdown showed that there were no significant priming effects in our two youngest age groups (third and fifth graders). In high schoolers and adults, however, priming was greater in the transparent compound condition than in the noncompound condition (high schoolers: $z = 2.32$, $p = .020$; adults: $z = 3.16$, $p = .002$), greater in the opaque compound condition than in the noncompound condition (high schoolers: $z = 2.65$, $p = .008$; adults: $z = 1.97$, $p = .049$), and comparable in the two compound conditions (high schoolers: $z = 0.05$, $p = .958$; adults: $z = 1.24$, $p = .216$), thereby confirming the pattern seen in the overall error data analyses.

Discussion

Recent studies have pointed to the importance of embedded stems in children's reading development (e.g., Beyersmann, Grainger, et al., 2015; Hasenäcker et al., 2016; Nation & Cocksey, 2009), and it has been suggested that because of this children may begin to apply more automatic processes of morphological segmentation to compound words earlier in their reading development than in the case of affixed words (Grainger & Beyersmann, 2017). The aim or our study was to test this hypothesis by examining the developmental trajectory of compound segmentation effects in primary school children, high school students, and adults. Children and adults participated in a masked priming study comparing transparent compound (*farmhouse–farm*), opaque compound (*butterfly–butter*), and noncompound (*sandwich–sand*) priming effects relative to an unrelated control. The results showed significant and equal priming effects in the two compound conditions, which was mainly reflected in the RT analyses but also partially supported by the error analyses. Moreover, priming in the transparent and opaque compound conditions was significantly larger than in the noncompound priming condition. This pattern was clearly and unequivocally observed across all participants, including third graders, fifth graders, high schoolers, and adults (see Fig. 1).

Several conclusions can be derived from the current findings. First, the absence of priming in the noncompound condition indicates that the observed priming effects are not simply due to lower-level form prime–target overlap, which is consistent with previous affixed word priming studies with children (e.g., Beyersmann, Castles, et al., 2012; Schiff et al., 2012) and adults (e.g., Beyersmann, Ziegler, et al., 2016; Longtin, Segui, & Hallé, 2003; Rastle et al., 2004). Priming was significantly greater in the two compound conditions compared with the noncompound condition, thereby providing

[4] Although target words were matched across item types, it is possible that the psycholinguistic measures were not sufficiently fine-tuned to capture changes across age groups (e.g., changes in word frequency), which would explain why the effect of item type varied across participant groups.

confirmatory evidence for the important role of morphological processing in skilled readers. Second, priming emerged independent of whether the prime and target were semantically related (*farmhouse–farm*) or not (*butterfly–butter*), suggesting that both transparent and opaque compound words were rapidly decomposed into morphemic subunits independent of semantics. Third, priming occurred with very brief prime presentation durations (50 ms), such that participants were unable to consciously identify and process the prime, indicating that the observed compound priming effects tap into the early automatic stages of reading.

Thus, our results provide evidence for a highly automatized form of compound word segmentation in young children, which is already evident in children as young as Grade 3. One explanation for the early emergence of embedded stem priming effects may be that children make use of their prior knowledge of free-standing words to identify them in an embedded word context. Children are likely to be exposed to morphologically simple words (*paint*) earlier in their reading development than morphologically complex words (*painter*) (Rastle, 2018). This means that at the start of reading instruction they would quickly map the newly acquired orthographic forms (*farm, house,* and *farmhouse*) onto the already existing lexical representations (from their oral vocabulary). Reading a word like *butterfly* would then activate not only the representation of the word itself but also the representations of the embedded words *butter* and *fly*. The activation of embedded words would emerge simply by drawing on knowledge of free-standing words without the requirement for any specialized morphemic representations, which explains why the embedded stem priming effects emerge so readily in our youngest participants. We further argue that the reason for the absence of priming for the noncompound primes (e.g., *sandwich–sand*) is that what remains once the embedded word has been removed (i.e., *wich*) is not a word. In other words, this condition, contrary to the transparent and opaque compound priming conditions, does not comply with the principle of full decomposition.

As children then become more fluent readers, the morphological parsing system will become more proficient in rapidly identifying affixes, with some initial evidence from Schiff et al. (2012) that these effects emerge in high schoolers—and we certainly know that adults are experts at this (Amenta & Crepaldi, 2012; Beyersmann, Ziegler, et al., 2016; Rastle & Davis, 2008). An explanation for the comparatively late emergence of affix-stripping mechanisms is offered by Grainger and Beyersmann's (2017) theoretical framework, suggesting that children use embedded stems as a bootstrapping mechanism for morphological parsing during reading development. It is the early use of embedded stems that is thought to drive the transparent and opaque compound priming effects seen in the current study in the youngest readers as well as in the transparent suffixed word priming effects reported in prior research. The reported absence of pseudo-suffixed word priming in young readers is explained by the later acquisition of affix representations relative to stem representations when learning to read. According to Grainger and Beyersmann (2017), the absence of affix representations allows lateral inhibitory interactions to fully operate between the embedding word and the embedded word when these are not morphologically related, hence impeding activation of the embedded word in pseudo-suffixed primes. This does not occur for opaque compound primes because the principle of full decomposition compensates for any such inhibitory influences. The later acquisition of affix representations during reading development then enables the principle of full decomposition to compensate for such inhibitory influences with pseudo-suffixed primes, thereby allowing these priming effects to emerge in older children.

The results of Hasenäcker et al. (2017) provided some initial support for this hypothesized difference in developmental trajectories for the processing of compound words and suffixed words by showing the emergence of compound effects prior to the effects of suffixed words. With respect to masked priming, Grainger and Beyersmann (2017) theoretical framework makes the clear prediction that opaque compound priming effects (e.g., *butterfly–butter*) should be found in children who do not show pseudo-suffixed word priming (e.g., *corner–corn*). Although the general pattern of findings so far is in line with this prediction (e.g., Beyersmann, Castles, et al., 2012; Schiff et al., 2012), this has yet to be directly tested.

The robustness of priming effects across all age groups, including the most skilled group of adult participants, suggests that the early-acquired embedded stem priming effects are not compromised by the later acquisition of morphological parsing mechanisms that we typically see in adults. The automatic activation of embedded stems clearly continues to play a central role within the skilled reading system. One possibility is that the activation of compound word representations (*farmhouse, butterfly*) is always mediated by prior access to the decomposed entries (*farm* + *house, butter* + *fly*), which would be consistent with single pathway theories of morphological processing (e.g., Crepaldi, Rastle, Coltheart, & Nickels, 2010; Rastle & Davis, 2008; Taft, 2003). Single-pathway theories posit that complex words are initially mapped onto prelexical representations of the constituent morphemes (*farm* and *house*), which then activate the whole word (*farmhouse*) in the orthographic lexicon. Alternatively, it is also possible that compound word representations and decomposed entries are available in separate pathways, as postulated by parallel dual-route theories (e.g., Baayen & Schreuder, 1999; Beyersmann, Coltheart, & Castles, 2012; Diependaele, Sandra, & Grainger, 2009). Indeed, robust whole-word frequency and constituent frequency effects in Finnish compound word reading provide further evidence in favor of the simultaneous processing of constituent morphemes and whole words (e.g., Bertram & Hyönä, 2003; Pollatsek & Hyönä, 2005).

In summary, our data provide evidence for a reading mechanism that enables children to rapidly decompose compound words into their embedded word constituents. This skill is acquired early in children's reading development at a stage when they are still learning to master basic reading skills. It is possible that embedded word activation mechanisms are acquired earlier in nonagglutinative Latinate languages such as English where embedded stems are likely to occur in the edge-aligned position (e.g., left aligned as in *packing*, right aligned as in *unpack*), such that spaces can be used as orthographic anchor points (Grainger & Beyersmann, 2017). In more agglutinative languages such as Finnish and German, a larger number of words have more than two morphemes, such that embedded stems often appear in a non-edge-aligned position (*dis-cover-ing*), and in Semitic languages such as Hebrew, where stems are noncontiguous consonant strings (*zkr* in *tizkoret*). This might make it more difficult to extract embedded words, thereby predicting that opaque compound priming effects should emerge at later developmental stages within those languages. A logical extension of our current work, therefore, would be the examination of different developmental trajectories of compound decomposition effects in languages like Finnish and Hebrew to shed further light on the orthographic constraints involved in children's acquisition of embedded word activation mechanisms.

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Appendix A

Items used in the study

Transparent compound condition:
AIR, airplane, township; CARE, carefree, doughnut; CROSS, crossover, southwest; EARTH, earthquake, background; EYE, eyebrow, carpool; FOOT, footrest, starfish; FORK, forklift, charcoal; GRASS, grassland, framework; GRAVE, graveyard, sunflower; HAND, handbag, keyhole; HEAD, headache, notebook; MOON, moonlight, stagehand; MOTOR, motorcycle, friendship; PATCH, patchwork, waistline; PIG, pigtail, tadpole; POP, popcorn, sixfold; POST, postcard, scrabble; RAIL, railroad, fuselage; SAUCE, saucepan, cannibal; SHOE, shoelace, billiard; SKATE, skateboard, deficiency; SNOW, snowball, generous; SUN, sunroof, hamster; TABLE, tableware, artichoke; TEA, teacup, friend; TEAM, teamwork, tapestry; TEXT, textbook, bulletin; TOOL, toolbox, between; TOOTH, toothpaste, conference; WALL, wallpaper, astronaut; WEEK, weekday, million; WIDE, widespread, calculator

Opaque compound condition:
BLACK, blacksmith, pickpocket; BLOW, blowfish, softball; BLUE, blueprint, stopwatch; *BREAK, breakfast, flowerpot; BUTTER, butterfly, fishbowl; CAP, capsize, earring; CART, cartridge, northeast; COCK, cocktail, hometown; CROW, crowbar, lawsuit; DEAD, deadline, passport; EGG, eggplant, heirloom; FLAP, flapjack, paycheck; FORT, fortnight, household; HAM, hamstring, sideburns; HIGH, highway, rainbow; HONEY, honeymoon, turntable; JACK, jackpot, fortune; JOY, joystick, humility; MEAN, meantime, canister; MUSH, mushroom, camomile; PEPPER, peppermint, formidable; PINE, pineapple, spaghetti; PUMP, pumpkin, barrier; RAN, ransack, textile; SEA, seasaw, finger; SHORT, shortbread, instrument; SLAP, slapstick, ambulance; SPEAR, spearmint, carpenter; STEP, stepson, battery; STRAW, strawberry, enthusiasm; TREAD, treadmill, harmonica; HORSE, horseradish, caterpillar
Noncompound condition:
ART, artificial, basketball; *COIN, coincidence, wheelbarrow; BOOM, boomerang, steamship; CAMP, campaign, ashtray; CARD, cardigan, bookmark; PART, particular, drawbridge; TOUR, tournament, brainstorm; *COURT, courtesy, telltale; *CAT, cathedral, jellyfish; *CHAMP, champagne, briefcase; LET, lettuce, airport; LOT, lottery, bathtub; MAIN, maintain, cupboard; *MATE, material, doorstop; MUST, mustard, beeline; *PALE, palette, bedroom; PART, partner, century; *PEN, penguin, hammock; PORT, portray, captain; *MET, meteorite, battalion; SCAN, scandal, capsule; SHALL, shallow, kitchen; SHUT, shuttle, wallaby; SOLD, soldier, library; COST, costume, tantrum; TROLL, trolley, country; VAN, vanilla, clothes; SAT, satellite, humiliate; CHUCK, chuckle, vampire; PASS, passenger, character; SAND, sandwich, antennae; STAND, standard, barbecue

Note. Targets are listed in uppercase; each target is followed by its corresponding related prime and then by its unrelated prime, both in lowercase. Prime–target pairs that varied in phonological form are indicated by an asterisk.

Appendix B

(a) Mean lexical decision times (ms) across participants and standard deviations for each age group

	Transparent		Opaque		Form	
	Related	Unrelated	Related	Unrelated	Related	Unrelated
	snowball–SNOW	passport–SNOW	butterfly–BUTTER	household–BUTTER	sandwich–SAND	vampire–SAND
Adults (n = 48)						
Mean	530	565	553	596	564	576
SD	60	67	64	84	71	71
Effect size	35		43		12	
High schoolers (n = 34)						
Mean	603	649	631	679	641	647
SD	89	89	103	120	91	88
Effect size	46		48		6	
Fifth graders (n = 46)						
Mean	881	929	954	991	955	965
SD	182	177	179	218	183	186
Effect size	48		37		10	

(*continued on next page*)

(*continued*)

	Transparent		Opaque		Form	
	Related	Unrelated	Related	Unrelated	Related	Unrelated
	snowball–SNOW	passport–SNOW	butterfly–BUTTER	household–BUTTER	sandwich–SAND	vampire–SAND
Third graders (n = 33)						
Mean	1123	1162	1175	1199	1195	1206
SD	296	340	352	304	339	294
Effect size	39		24		11	

(b) Mean error rates (%) across participants and standard deviations (SD) for each age group.

	Transparent		Opaque		Form	
	Related	Unrelated	Related	Unrelated	Related	Unrelated
	snowball–SNOW	passport–SNOW	butterfly–BUTTER	household–BUTTER	sandwich–SAND	vampire–SAND
Adults (n = 48)						
Mean	3.1	6.9	4.8	7.2	7.7	7
SD	5.3	7.3	6.9	10	8.9	9.4
Effect size	3.8		2.4		−0.7	
High schoolers (n = 34)						
Mean	2.4	4.7	3.6	7.3	6.1	4.8
SD	3.4	6	4.4	7.3	7.6	5.3
Effect size	2.3		3.7		−1.3	
Fifth graders (n = 46)						
Mean	4.1	4.5	9.8	9.6	7.2	7.1
SD	6.1	6.8	9.5	7.9	7	7
Effect size	0.4		−0.2		−0.1	
Third graders (n = 33)						
Mean	10.2	8.5	13.3	14.2	13.4	10.8
SD	10	11	12	9	9	10
Effect size	−1.7		0.9		−2.6	

References

Amenta, S., & Crepaldi, D. (2012). Morphological processing as we know it: An analytical review of morphological effects in visual word identification. *Frontiers in Psychology, 3*. https://doi.org/10.3389/fpsyg.2012.00232.

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. Cambridge, UK: Cambridge University Press.

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

Baayen, R. H., Piepenbrock, R., & van Rijn, H. (1993). *The CELEX lexical database (CD–ROM)*. Philadelphia: Linguistic Data Consortium, University of Pennsylvania.

Baayen, R. H., & Schreuder, R. (1999). War and peace: Morphemes and full forms in a noninteractive activation parallel dual-route model. *Brain and Language, 68*, 27–32.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*, 255–278.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). lme4: Linear mixed-effects models using "Eigen" and S4 (R package Version 1.1-5). Retrieved from <http://CRAN.R-project.org/package=lme4>.

Bertram, R., & Hyönä, J. (2003). The length of a complex word modifies the role of morphological structure: Evidence from eye movements when reading short and long Finnish compounds. *Journal of Memory & Language, 48*, 615–634.
Bertram, R., Laine, M., & Virkkala, M. M. (2000). The role of derivational morphology in vocabulary acquisition: Get by with a little help from my morpheme friends. *Scandinavian Journal of Psychology, 41*, 287–296.
Beyersmann, E., Casalis, S., Ziegler, J. C., & Grainger, J. (2015). Language proficiency and morpho-orthographic segmentation. *Psychonomic Bulletin & Review, 22*, 1054–1061.
Beyersmann, E., Castles, A., & Coltheart, M. (2012). Morphological processing during visual word recognition in developing readers: Evidence from masked priming. *Quarterly Journal of Experimental Psychology, 65*, 1306–1326.
Beyersmann, E., Cavalli, E., Casalis, S., & Colé, P. (2016). Embedded stem priming effects in prefixed and suffixed pseudowords. *Scientific Studies of Reading, 20*, 220–230.
Beyersmann, E., Coltheart, M., & Castles, A. (2012). Parallel processing of whole-words and morphemes in visual word recognition. *Quarterly Journal of Experimental Psychology, 65*, 1798–1819.
Beyersmann, E., Grainger, J., Casalis, S., & Ziegler, J. C. (2015). Effects of reading proficiency on embedded stem priming in primary school children. *Journal of Experimental Child Psychology, 139*, 115–126.
Beyersmann, E., Ziegler, J. C., Castles, A., Coltheart, M., Kezilas, Y., & Grainger, J. (2016). Morpho-orthographic segmentation without semantics. *Psychonomic Bulletin & Review, 23*, 533–539.
Bowers, J., & Bowers, P. (2018). The importance of correctly characterizing the English spelling system when devising and evaluating methods of reading instruction: Comment on Taylor, Davis, and Rastle (2017). Quarterly Journal of Experimental Psychology. Advance online publication. doi: 10.1177/1747021818759477.
Burani, C., Marcolini, S., & Stella, G. (2002). How early does morpholexical reading develop in readers of a shallow orthography? *Brain and Language, 81*, 568–586.
Carlisle, J. F. (1988). Knowledge of derivational morphology and spelling ability in fourth, sixth and eighth graders. *Applied Psycholinguistics, 9*, 247–266.
Carlisle, J. F. (2000). Awareness of the structure and meaning of morphologically complex words: Impact on reading. *Reading and Writing, 12*, 169–190.
Carlisle, J. F., & Katz, L. (2006). Effects of word and morpheme familiarity on reading of derived words. *Reading and Writing, 19*, 669–693.
Casalis, S., Quemart, P., & Duncan, L. G. (2015). How language affects children's use of derivational morphology in visual word and pseudoword processing: Evidence from a cross-language study. *Frontiers in Psychology, 6*. https://doi.org/10.3389/fpsyg.2015.00452.
Castles, A., Rastle, K., & Nation, K. (2018). Ending the "Reading Wars": Reading acquisition from novice to expert. *Psychological Science in the Public Interest, 19*(1), 5–51.
Crepaldi, D., Rastle, K., Coltheart, M., & Nickels, L. (2010). "Fell" primes "fall", but does "bell" prime "ball"? Masked priming with irregularly-inflected primes. *Journal of Memory and Language, 63*, 83–99.
Dawson, N., Rastle, K., & Ricketts, J. (2018). Morphological effects in visual word recognition: Children, adolescents, and adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44*, 645–654.
Deacon, S. H., & Bryant, P. (2006a). Getting to the root: Young writers' sensitivity to the role of root morphemes in the spelling of inflected and derived words. *Journal of Child Language, 33*, 401–417.
Deacon, S. H., & Bryant, P. (2006b). This turnip's not for turning: Children's morphological awareness and their use of root morphemes in spelling. *British Journal of Developmental Psychology, 24*, 567–575.
Diependaele, K., Sandra, D., & Grainger, J. (2009). Semantic transparency and masked morphological priming: The case of prefixed words. *Memory & Cognition, 37*, 895–908.
Fiorentino, R., & Fund-Reznicek, E. (2009). Masked morphological priming of compound constituents. *The Mental Lexicon, 4*(2), 159–193.
Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35*, 116–124.
Grainger, J., & Beyersmann, E. (2017). Edge-aligned embedded word activation initiates morpho-orthographic segmentation. In B. H. Ross (Ed.). *The psychology of learning and motivation (Advances in Research and Theory)* (Vol. 67, pp. 285–317). San Diego: Elsevier Academic Press.
Grainger, J., Dufau, S., & Ziegler, J. C. (2016). A vision of reading. *Trends in Cognitive Science, 20*, 171–179.
Hasenäcker, J., Beyersmann, E., & Schroeder, S. (2016). Masked morphological priming in German-speaking adults and children: Evidence from response time distributions. *Frontiers in Psychology, 7*. https://doi.org/10.3389/fpsyg.2016.00929.
Hasenäcker, J., Schroeter, P., & Schroeder, S. (2017). Investigating developmental trajectories of morphemes as reading units in German. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*, 1093–1108.
Kemp, N., & Bryant, P. (2003). Do beez buzz? Rule-based and frequency-based knowledge in learning to spell plural-s. *Child Development, 74*, 63–74.
Kliegl, R., Masson, M. E. J., & Richter, E. M. (2010). A linear mixed model analysis of masked repetition priming. *Visual Cognition, 18*, 655–681.
Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2014). lmerTest: Tests in linear mixed effects models (R package Version 2.0-6). Retrieved from <http://CRAN.R-project.org/package=lmerTest>.
Landauer, T. K., & Dumais, S. T. (1997). A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological Review, 104*, 211–240.
Longtin, C. M., Segui, J., & Hallé, P. A. (2003). Morphological priming without morphological relationship. *Language and Cognitive Processes, 18*, 313–334.
Masterson, J., Stuart, M., Dixon, M., & Lovejoy, S. (2010). Children's Printed Word Database: Continuities and changes over time in children's early reading vocabulary. *British Journal of Psychology, 101*, 221–242.
Nation, K., & Cocksey, J. (2009). Beginning readers activate semantics from sub-word orthography. *Cognition, 110*, 273–278.
National Reading Panel (2000). *Teaching children to read: An evidence based assessment of the scientific research literature on reading and its implications for reading instruction*. Washington, DC: National Institute of Child Health and Human Development.

Pacton, S., Foulin, J. N., Casalis, S., & Treiman, R. (2013). Children benefit from morphological relatedness when they learn to spell new words. *Frontiers in Psychology, 4*. https://doi.org/10.3389/fpsyg.2013.00696.
Pacton, S., Jaco, A. A., Nys, M., Foulin, J. N., Treiman, R., & Peereman, R. (2018). Children benefit from morphological relatedness independently of orthographic relatedness when they learn to spell new words. *Journal of Experimental Child Psychology, 171*, 71–83.
Perdijk, K., Schreuder, R., Baayen, R. H., & Verhoeven, L. (2012). Effects of morphological family size for young readers. *British Journal of Developmental Psychology, 30*, 432–445.
Pollatsek, A., & Hyönä, J. (2005). The role of semantic transparency in the processing of Finnish compound words. *Language and Cognitive Processes, 20*, 261–290.
Quémart, P., Casalis, S., & Colé, P. (2011). The role of form and meaning in the processing of written morphology: A priming study in French developing readers. *Journal of Experimental Child Psychology, 109*, 478–496.
R Development Core Team (2008). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
Rastle, K. (2018). The place of morphology in learning to read in English. *Cortex*. https://doi.org/10.1016/j.cortex.2018.02.008.
Rastle, K., & Davis, M. H. (2008). Morphological decomposition based on the analysis of orthography. *Language and Cognitive Processes, 23*, 942–971.
Rastle, K., Davis, M. H., & New, B. (2004). The broth in my brother's brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin & Review, 11*, 1090–1098.
Rastle, K., & Taylor, J. S. H. (2018). Print–sound regularities are more important than print–meaning regularities in the initial stages of learning to read: Response to Bowers & Bowers (2018). *Quarterly Journal of Experimental Psychology*, 71. https://doi.org/10.1177/1747021818775053.
Roman, A. A., Kirby, J. R., Parrila, R. K., Wade-Woolley, L., & Deacon, S. H. (2009). Toward a comprehensive view of the skills involved in word reading in Grades 4, 6, and 8. *Journal of Experimental Child Psychology, 102*, 96–113.
Schiff, R., Raveh, M., & Fighel, A. (2012). The development of the Hebrew mental lexicon: When morphological representations become devoid of their meaning. *Scientific Studies of Reading, 16*, 383–403.
Snell, J., Grainger, J., & Declerck, M. (2018). A word on words in words: How do embedded words affect reading? *Journal of Cognition, 1*. https://doi.org/10.5334/joc.45.
Taft, M. (2003). Morphological representation as a correlation between form and meaning. In E. Assink & D. Sandra (Eds.), *Reading complex words* (pp. 113–137). Amsterdam: Kluwer.
Taylor, J. S. H., Davis, M. H., & Rastle, K. (2017). Comparing and validating methods of reading instruction using behavioural and neural findings in an artificial orthography. *Journal of Experimental Psychology: General, 146*, 826–858.
Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *Test of word reading efficiency*. Austin, TX: Pro-Ed.
Wechsler, D. (1997). *Wechsler adult intelligence scale-third edition (WAIS-III)*. San Antonio, TX: Psychological Corporation.