Finding the man amongst many: A developmental perspective on mechanisms of morphological decomposition

Nicola Dawson *, 1, Kathleen Rastle, Jessie Ricketts

Royal Holloway, University of London, United Kingdom

ARTICLE INFO

Keywords:
Reading development
Visual word recognition
Morphology
Adolescents
Cross-sectional

ABSTRACT

Skilled reading is characterized by rapid recognition of morphologically complex words. Evidence suggests that adult readers segment complex words into their constituent morphemes during visual word recognition, and that this extends to items that have only a surface morphological structure (e.g., corner), a process termed ‘morpho-orthographic segmentation’. It is not yet known how and when this mechanism is established over the course of reading development, although data from English-speaking children suggest that it may be a relatively late-acquired milestone. The purpose of this study was to examine for the first time the mechanisms driving morphological processing across late childhood and adolescence. A cross-sectional sample of 204 children and adolescents from South-East England, ranging in age from 9 to 18 years (M age = 13.74 years, SD = 2.68; 110 female), completed a visual masked prime lexical decision task using three sets of prime-target pairs: morphological (e.g., teacher – TEACH), pseudomorphological (sharing an apparent morphological relationship in the absence of a semantic relationship, e.g., corner – CORN), and form (sharing an orthographic relationship only, e.g., window – WIND). Linear mixed effects models revealed both morphological and pseudomorphological priming in the absence of form priming, with priming magnitude increasing in line with age, and stronger evidence of morpho-orthographic segmentation emerging in line with word reading efficiency. Our findings reveal advances in the reading system during adolescence which may reflect accumulated exposure to regularities in the writing system, facilitating rapid access to meaning from print.

1. Introduction

Reading is one of the most valuable skills a child will acquire in their lifetime. The ability to translate symbols on a page into meaning opens doors to education, employment and culture, and understanding how children become skilled readers has thus been a major focus of literacy research. In early reading development, children learn mappings between letter patterns and sound patterns, equipping them with the tools that they need to decode words (Duff, Mengoni, Bailey, & Snowling, 2014). With practice, children build knowledge of visual word forms so that word reading is increasingly efficient (Ehri, 2005b; Share, 1995). However, relative to the wealth of evidence on children’s knowledge about spelling-sound regularities, less is known about these later stages of reading development (Castles, Rastle, & Nation, 2018).

Our understanding of how readers move from novice to expert is limited in part by a paucity of data from adolescent readers. It is also constrained by theoretical models of reading, which have focused predominately on processing of monosyllabic words (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 2004; Perry, Ziegler, & Zorzi, 2007). One consequence of this is that a second source of regularity in the English writing system has largely been overlooked in theories of reading development: the links between spelling and meaning brought about by morphological relationships (Rastle, 2019b). It is well established that skilled readers capitalize on morphemes while reading words (Amenta & Crepaldi, 2012), yet developing readers of English do not demonstrate the same rapid analysis of morphological structure (Beyersmann, Castles, & Coltheart, 2012; Dawson, Rastle, & Ricketts, 2018). It is not yet known what changes occur over the course of reading development in relation to children’s representation of morphological information, or why these changes occur. The aim of the

* Corresponding author.

E-mail address: nicola.dawson@psy.ox.ac.uk (N. Dawson).

1 Note that the first author is now based at the University of Oxford. Correspondence should be addressed to Nicola Dawson, Department of Experimental Psychology, University of Oxford, Anna Wats Building, Radcliffe Observatory Quarter, Woodstock Road, Oxford, OX2 6GG, United Kingdom. Email: nicola.dawson@psy.ox.ac.uk. Our data are available on the Open Science Framework at: https://osf.io/3g7vx/?view_only=f2032dc3182e43dd784c2738fa3592ae8.

https://doi.org/10.1016/j.cognition.2021.104605

Received 27 September 2018; Received in revised form 10 January 2021; Accepted 13 January 2021
Available online 20 February 2021
0010-0277/ © 2021 Published by Elsevier B.V.
present study is to examine the mechanisms underpinning morphological processing in visual word recognition in a cross-sectional sample of 204 children and adolescents ranging in age from 9-18 years.

Morphemes are commonly defined as the smallest meaningful unit in a word (Sánchez-Gutierrez, Mailhot, Deacon, & Wilson, 2018). Morphologically-complex words (e.g., unbreakable) comprise multiple morphemes, usually combining a stem (break) and one or more affixes (un- and -able). As children’s reading skills develop, complex words constitute an increasingly large proportion of words encountered in texts (Nagy & Anderson, 1984). In English, spellings represent morphemic as well as phonemic units, such that the pronunciation of words cannot always be predicted from principles of spelling-sounds mappings (Bryant & Nunes, 2004). For example, homophones passed and past are spelled differently because the former preserves the –ed inflection denoting past tense.

Repeated studies have demonstrated that skilled adult readers process complex words on the basis of morphological structure during visual word recognition. Factors such as morphological family size (the number of different words derived from a given stem; Schreuder & Baayen, 1997) and stem frequency (Taft & Ardasinski, 2006) influence the time taken to recognize morphologically simple and complex words respectively. In priming experiments, words preceded by a morphological relative (e.g., teacher – TEACH) produce faster response times than the same word preceded by an unrelated prime, and this effect cannot be explained by simple overlap in form and meaning (Rastle, Davis, Marslen-Wilson, & Tyler, 2000). Conversely, morphologically-structured nonword items (e.g., earist) are more difficult to reject in visual lexical decision tasks than matched non-morphologically structured items (e.g., earlit), indicating that morphemic representations are activated regardless of lexical status (Crepaldi, Rastle, & Davis, 2010; Taft & Forster, 1975). Together, these findings have been taken to show that morphologically-structured letter strings are decomposed during visual word recognition (e.g., teacher + er), and that complex words are stored in decomposed form in the lexicon (e.g., Taft & Forster, 1975, but cf. Gonnerman, Seidenberg, & Andersen, 2007; Quémart, Gonnerman, Downing, & Deacon, 2017).

An important question is whether morphological decomposition is dependent on the semantic relationship between the complex word and its stem, as this provides insight into the underlying processes driving these morphological effects. In sublexical models of morphological processing, which predominantly adopt a localist framework (e.g., the AUSTRAL model; Taft, 2006, Taft & Nguyen-Hoan, 2010), processing of complex words takes place at two levels: firstly at an orthographic level, where complex words undergo obligatory decomposition into their constituent morphemes, and secondly at a lexical level, where activation from these orthographic units combines with feedback from semantic and syntactic information (for a similar account, see Crepaldi, Rastle, Coltheart, & Nickels, 2010). Sublexical models thus predict that pseudomorphological items such as corner, which are monomorphemic but comprise an existing stem (corn) and affix (-er), are segmented in the initial stages of word recognition just as true morphological items (e.g., teacher) are, despite the fact that teach and teacher are related in meaning, while corn and corner are not. This process is known as ‘morpho-orthographic segmentation’ (Rastle, Davis, & New, 2004; see also Rastle & Davis, 2008), and on this perspective, the influence of the semantic relationship between the complex word and its stem only emerges in the later stages of visual word processing (Rastle et al., 2018).

Empirical support for sublexical approaches to morphological decomposition comes predominantly from masked priming studies in which skilled readers respond to targets that are primed by a true morphological relative (e.g., teacher – TEACH), a pseudomorphological relative (e.g., corner – CORN, in which –er is an English suffix, but prime and target do not share a semantic relationship) and a prime related only in form (e.g., window – WIND, in which –ow is not an English suffix). Crucially, presentation of the prime is very brief (typically less than 50 ms) and follows a series of hash symbols which act as a forward mask, meaning that participants are normally unaware of the presence of the prime. Unlike cross-modal or visible priming experiments, this set-up permits exploration of the earliest stages of visual word recognition by minimizing the likelihood that the prime is available for conscious analysis (Forster & Davis, 1984). In adult readers, such tasks have usually revealed priming effects for targets preceded by morphological and pseudomorphological primes, which exceed the degree of priming observed in the form-only condition (Rastle et al., 2004; see also Longtin, Segui, & Hallé, 2003 for similar findings in French readers). This pattern of findings has been interpreted as evidence that both morphological (teacher) and pseudomorphological (corner) items undergo morpho-orthographic segmentation, and that this effect is not simply a consequence of orthographic overlap, due to an absence of priming in the form condition (Rastle & Davis, 2008).

Sublexical accounts of morphological decomposition were developed based on skilled adult reading, but there has been far less examination of these processes in developing readers. The issue is an important one: accumulating evidence indicates that morphological knowledge is central to reading development beyond early childhood, and in particular, to the emergence of skilled reading via a direct print-to-meaning pathway (see Rastle, 2019b for an overview). The ability to detect and manipulate morphemes in words (known as ‘morphological awareness’) is already evident by 8-9 years (e.g., Carlisle, 2000), and is closely linked with a number of literacy outcomes, including spelling (Deacon, Kirby, & Casselbell-Bell, 2009; Nunes, Bryant, & Bindman, 1997), vocabulary (Anglin, 1993), word reading (Kirby et al., 2012; Kruk & Bergman, 2013; Nagy, Berninger, & Abbott, 2006; Singson, Mahony, & Mann, 2000), and reading comprehension (Carlisle, 2000; Carlisle & Fleming, 2003; Kirby et al., 2012; Nagy et al., 2006). However, there is currently little understanding of how children acquire and represent morphological knowledge in a way that supports rapid processing of complex words.

In the context of visual word recognition, sensitivity to morphological structure has been demonstrated across languages in children aged around 7-10 years (Burani, Marcolini, & Stella, 2002; Dawson et al., 2018; Lázaro, Camacho, & Burani, 2013; Perdijk, Schreuder, Baayen, & Verhoeven, 2012; Quémart, Casalis, & Duncan, 2012). Yet knowledge of morphological patterns is acquired and refined over time, and exposure to words in print is likely to be crucial for building representations that are activated independent of semantic context. In their model of morphological processing, Schreuder and Baayen (1995) proposed that an important stage in acquiring morphological knowledge is the development of representations of bound morphemes (e.g., affixes). They argued that as children’s vocabulary knowledge grows, they are increasingly exposed to form-meaning regularities across words sharing an affix (e.g., farmer is a person who farms, teacher is a person who teaches). Based on these regularities, children develop a conceptual representation of the affix (agent that performs the action), and subsequently build an association between that conceptual representation and the letter string that represents it (–er), culminating in a form-based ‘access representation’. Support for the idea that children’s knowledge of affixes undergoes a protracted period of consolidation comes from recent evidence indicating that children make use of embedded stem activation when processing morphologically-structured pseudowords, whereas skilled adult readers benefit from the combination of a stem and suffix (Beyersmann, Grainger, Casalis, & Ziegler, 2015; Beyersmann, Grainger, & Castles, 2019; Grainger & Beyersmann, 2017; Hasnæcker, Beyersmann, & Schroeder, 2016; Lázaro et al., 2018; Meunier & Longtin, 2007).

Empirical examination of morpho-orthographic segmentation in developing readers has produced mixed findings. In their study, Beyersmann et al. (2012) adopted the paradigm established by Rastle et al. (2004) to investigate whether there was evidence of morpho-orthographic segmentation in readers aged 8-11 years. They found priming effects for word pairs that shared a true morphological
relationship, but not for those sharing a pseudomorphological or form relationship. In their older age group (10-11 years), they further observed an inhibitory priming effect for form-related pairs: responses to targets preceded by a related prime were slower than to those preceded by an unrelated prime. This differed from the pattern of findings in their adult controls, who showed priming effects in the morphological and pseudomorphological conditions, but not in the form condition (although the magnitude of priming was greater in the morphological than the pseudomorphological condition). These data support the view that morpho-orthographic segmentation processes emerge relatively late in reading development. This conclusion resonates more broadly with ERP data indicating that efficiency in form-level processing is still developing at the age of 12 years (Eddy, Grainger, Holcomb, Mitra, & Gabrieli, 2014). It also aligns with neuroimaging data showing that regions of the brain comprising the ventral pathway for reading, associated with direct spelling-meaning mappings and more recently, with morphological processing in skilled readers (Yablonski, Rastle, Taylor, & Ben-Shachar, 2018), continue to develop into mid-adolescence (Ben-Shachar, Dougherty, Deutsch, & Wandell, 2011).

In contrast to the pattern of priming observed with English-speaking children, Quemart, Casalis, and Colé (2011) found that French children aged 8-12 years showed equivalent priming across true morphological and pseudomorphological word pairs. These data suggest that contrary to Beyersmann et al.’s (2012) findings, participants did rely on surface morphological structure when processing complex words. This discrepancy may be explained in part by evidence indicating cross-linguistic differences in efficiency of morphological processing.

### Table 1
Mean orthographic overlap, word length, orthographic neighborhood size and frequency for stimuli across conditions (after Beyersmann et al., 2012)

| Property                        | Morphological | Pseudomorphological | Form |
|---------------------------------|---------------|---------------------|------|
| Orthographic prime-target overlap | 1.61 (0.26)   | 1.47 (0.20)         | 1.50 (0.27) |
| Prime length (letters)         | 5.71 (0.63)   | 5.74 (0.96)         | 5.47 (0.90) |
| Prime orthographic N            | 2.85 (1.97)   | 2.24 (2.16)         | 2.74 (3.17) |
| Prime log frequency            | 1.38 (0.60)   | 1.61 (0.73)         | 1.32 (0.73) |
| Target length (letters)        | 3.62 (0.65)   | 3.94 (0.74)         | 3.71 (0.58) |
| Target orthographic N          | 8.82 (4.69)   | 8.82 (5.43)         | 9.97 (5.29) |
| Target log frequency           | 1.80 (0.46)   | 1.86 (0.84)         | 1.86 (0.82) |

**Note.** Standard deviations in parentheses.

a Prime length divided by target length.

b Calculated using CELEX in N-Watch (C. J. Davis, 2005).

### Table 2
Means and standard deviations for background measures by age group

| Measure                  | Children (9-10 years) | Younger adolescents (12-13 years) | Mid Adolescents (14-15 years) | Older adolescents (16-18 years) |
|--------------------------|-----------------------|-----------------------------------|-------------------------------|---------------------------------|
|                          | M         | SD       | M         | SD       | M         | SD       | M         | SD       |
| Nonverbal Ability        | 47.77     | 9.38     | 47.07     | 8.42     | 49.13     | 10.65    | 47.35     | 10.27    |
| Oral Vocabulary          | 53.85     | 10.84    | 50.89     | 8.46     | 52.38     | 5.93     | 52.43     | 8.93     |
| Sight Word Efficiency    | 99.38     | 9.70     | 100.04    | 12.59    | 100.77    | 13.71    | 100.33    | 12.16    |
| Phonemic Decoding Efficiency | 104.35   | 13.05    | 102.39    | 11.63    | 102.92    | 10.77    | 102.00    | 10.89    |

a T scores: $M = 50, SD = 10$.

b Standard scores: $M = 100, SD = 15$.

### Table 3
Mean percentage accuracy and raw RTs (outliers removed) by age group, condition and prime type

| Age group     | Condition | Prime type | Accuracy | RTs |
|---------------|-----------|------------|----------|-----|
|               |           |            | Mean     | SD  |
| Children      | Form      | Related    | 0.92     | 0.28 |
|               |           | Unrelated  | 0.94     | 0.24 |
|               | Pseudomorphological | Related | 0.90     | 0.30 |
|               |           | Unrelated  | 0.90     | 0.31 |
|               | Morphological | Related | 0.96     | 0.19 |
|               |           | Unrelated  | 0.95     | 0.22 |
| Younger adolescents | Form      | Related    | 0.93     | 0.25 |
|               |           | Unrelated  | 0.94     | 0.24 |
|               | Pseudomorphological | Related | 0.91     | 0.29 |
|               |           | Unrelated  | 0.94     | 0.24 |
|               | Morphological | Related | 0.97     | 0.16 |
| Mid adolescents | Form      | Related    | 0.94     | 0.23 |
|               |           | Unrelated  | 0.96     | 0.21 |
|               | Pseudomorphological | Related | 0.94     | 0.24 |
|               |           | Unrelated  | 0.94     | 0.24 |
|               | Morphological | Related | 0.97     | 0.17 |
| Older adolescents | Form      | Related    | 0.94     | 0.23 |
|               |           | Unrelated  | 0.96     | 0.21 |
|               | Pseudomorphological | Related | 0.96     | 0.18 |
|               |           | Unrelated  | 0.96     | 0.18 |
|               | Morphological | Related | 0.98     | 0.14 |
|               |           | Unrelated  | 0.98     | 0.16 |
between French and English-speaking children (Casalis, Quémart, & Duncan, 2015). However, Quémart et al.’s (2011) findings also contradict those of Beyersmann, Casalis, Ziegler, and Grainger (2015), who found that higher-proficiency French-speaking children relied on embedded stem activation and not morpho-orthographic segmentation to process morphologically-structured pseudowords.

From a theoretical perspective, understanding how children build knowledge of morphological relationships and how they activate this information in the context of reading provides a crucial step towards processing morphologically-structured pseudowords. Until now, the focus has been almost exclusively on developing readers in mid-late childhood or on skilled adult readers, but data from adolescent readers are crucial if we are to address this issue. Our aim was to investigate the mechanisms driving morphological decomposition in children and adolescents. Specifically, we used the paradigm established in previous masked priming studies (Beyersmann et al., 2012; Rastle et al., 2004) to examine whether there is evidence for a morpho-orthographic segmentation mechanism across this developmental period, and whether this is influenced by reading experience.

A cross-sectional design was used, which included children and adolescents ranging in age from 9 to 18 years, sampled from four age groups: children (9-10 years; Year 5 in the UK education system); younger adolescents (12-13 years; Year 8); mid adolescents (14-15 years; Year 10) and older adolescents (16-18 years; Years 12 and 13). These groups were similar in age to the children and adolescents included in Dawson et al. (2018), with the additional inclusion of mid-adolescent readers on the basis that this developmental period might be of particular interest in relation to morphological processing.

Robust morphological priming effects have been observed in both children and adults (e.g., Beyersmann et al., 2012; Rastle et al., 2004). Therefore, our first prediction (Hypothesis 1) was that across age groups we would observe stronger priming for targets sharing a true morphological relationship with their primes (teacher – TEACH), compared to primes and targets overlapping in orthography only (window – WIND), while if morpho-orthographic decomposition is dependent on reading experience, the same pattern may not be observed in the comparison between pseudomorphological (corner – CORN) and form priming. Given that pseudomorphological priming has been observed in adults (Longtin et al., 2003; Rastle et al., 2004), but not English-speaking children (Beyersmann et al., 2012), our second prediction (Hypothesis 2) was that pseudomorphological priming would increase in line with reading experience, as indexed by age. In addition to confirmatory analyses addressing these hypotheses, we ran exploratory models to examine the effect of reading ability on patterns of priming across the three conditions.

Table 4

| Predictors | Accuracy |
|-----------|----------|
|           | Odds Ratios | SE | z value | p   |
| Intercept | 24.56 | 3.68 | 21.37 | <.001 |
| Prime_type | 0.90 | 0.12 | -0.77 | .441 |
| Age_months | 1.23 | 0.09 | 2.78 | .005 |
| Condition_pseudomorphological | 0.94 | 0.19 | -0.52 | .606 |
| Condition_morphological | 2.01 | 0.41 | 3.36 | .001 |
| Prime_type x Age_months | 1.16 | 0.12 | 1.40 | .162 |
| Prime_type x | 0.88 | 0.15 | -0.72 | .472 |
| Condition_pseudomorphological | Prime_type x Condition_morphological | 1.38 | 0.27 | 1.66 | .097 |
| Age_months x | 1.10 | 0.09 | 1.19 | .234 |
| Condition_pseudomorphological | Prime_type x Age_months | 1.02 | 0.10 | 0.33 | .782 |
| Condition_pseudomorphological | Prime_type x Age_months x | 0.68 | 0.10 | -2.69 | .007 |
| Condition_morphological | Prime_type x Age_months x | 0.78 | 0.13 | -1.48 | .140 |

Random effects

\( \sigma^2 \)
\( \tau_{00} \) Punct
\( \tau_{00} \) Target
\( \tau_{11} \) Punct,Prime_type1
\( \tau_{11} \) Target,Prime_type1
\( \tau_{11} \) Target,Age_months
\( \rho_{01} \) Punct
\( \rho_{01} \) Target,Prime_type1
\( \rho_{01} \) Target,Age_months
\( \rho_{12} \) ICC
\( \eta_{pr} \)
\( \eta_{tar} \)
Observations

Marginal \( R^2 \)/ Conditional \( R^2 \)

.044 / .263

Note. The final model was structured as follows: Model <- glmer (log odds accuracy ~ condition * prime type * age months + (1 + prime type | participant) + (1 + prime type + age months | item)). p values less than .05 are indicated in bold.

* The intercept represents odds ratio for accuracy in the baseline (form) condition, averaged across age in months and prime type.
2. Method

2.1. Participants

A total of 204 children and adolescents from South-East England took part, ranging in age from 9 to 18 years (M age = 13.74 years, SD = 2.68; 110 female). Participants were sampled from four age groups: Children (9-10 years, M age = 9.77, SD = 0.27; n = 48, 20 female), younger adolescents (12-13 years, M age = 13.21, SD = 0.31; n = 57, 27 female), mid adolescents (14-15 years, M age = 14.65, SD = 0.33; n = 48, 23 female), and older adolescents (16-18 years, M age = 17.22, SD = 0.58; n = 51, 40 female). Note that children in England usually start learning to read at age 4 years.

Children were recruited from mainstream primary schools, and adolescents from mainstream secondary schools and sixth form educational settings (which provide non-compulsory advanced level qualifications for students aged 16-18). None of the participants had a recognized special educational need, and all spoke English as their first language. Sixth form college participants were entered into a prize draw to win a £25 Amazon voucher as a reward for participation. Informed consent was obtained from participants aged 16 years and over, and from parents of participants under 16 years. The study was approved by the University Research Ethics Committee at Royal Holloway, University of London.

2.2. Materials and procedure

2.2.1. Background measures

The main purpose of our background measures was to characterize the sample. Standardized assessments measuring nonverbal reasoning, vocabulary and word reading were administered according to manual instructions.

2.2.2. Nonverbal ability

This was measured using the Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence – Second Edition (WASI-II; Wechsler, 2013), in which participants select the image that completes a pattern.

Table 5
Comparing the effect of age on accuracy for related vs. unrelated primes, split by condition

| Outcome       | Contrast          | Condition            | Estimate | SE    | z ratio | p value |
|---------------|-------------------|----------------------|----------|-------|---------|---------|
| Accuracy      | Related - Unrelated | Morphological       | -0.10    | 0.14  | -0.75   | .454    |
|               | Related - Unrelated | Pseudomorphological | -0.23    | 0.10  | -2.36   | .018    |
|               | Related - Unrelated | Form                 | 0.15     | 0.11  | 1.40    | .162    |

Fig. 1. Plot showing raw inverted reaction time data points, smoothed conditional means and standard error by condition, prime type and age.
2.3.1. Stimuli

Stimuli were taken from Beyersmann et al. (2012) and comprised three sets of 34 prime-target pairs: morphological (sharing a true morphological relationship, e.g., teacher – TEACH), pseudomorphological (sharing an apparent morphological relationship in the absence of a semantic relationship, e.g., corner – CORN), and form (sharing an orthographic relationship only, e.g., window – WIND). The amount of orthographic overlap between prime and target was matched across conditions, as was word length in letters, orthographic neighborhood size (the number of words that can be generated by changing one letter of the target item; Coltheart, Davelaar, Jonasson, & Besner, 1977) and frequency for both primes and targets (Beyersmann et al., 2012). See Table 1 for a summary of stimuli characteristics.

Each target was also paired with an unrelated prime (e.g., robbery – TEACH), so that for each set of 34 targets, half were presented with a related prime and half with an unrelated prime. Prime-target pairings were counterbalanced across two lists, such that participants saw each target only once. Appendix A provides a full list of experimental stimuli. An additional 34 unrelated prime-target pairs (e.g., giving – ROPE) were included to reduce the proportion of related word pairs, as well as a set of 134 nonword targets for the purposes of the lexical decision task. Unrelated and nonword prime-target pairs were identical across the two lists.

2.3.2. Procedure

The masked priming task was completed individually or in pairs in a quiet area of school or sixth-form educational settings. Participants were presented with both written and verbal instructions informing them that they would see a series of real and nonsense words on the screen and that their task was to decide whether each was a real word or not as quickly as possible. DMDX (Forster & Forster, 2003) was used to present stimuli and record reaction times (RTs) and accuracy of responses. In each trial, a forward mask of hash symbols was presented for 800ms in the center of the screen, followed by the prime in lowercase font, which was displayed for 50ms in line with Beyersmann et al. (2012). This was followed by the target in uppercase font, which participants were asked to classify as either a real word or a nonword by pressing the right or left shoulder button respectively on a Gioteck VX-2 game controller. Target items remained on screen for a maximum of 5000ms, or until participants made a response. Prior to the experimental trials, participants were presented with eight practice items. Experimental trials were randomized, and included one break in the middle. In total, the masked priming task took approximately 10-15 minutes.

3. Results

Table 2 presents performance on background measures by age group. Mean T scores and standard scores on standardized assessments show
that performance for each age group is broadly in line with test norms. Below we present analyses examining the effects of prime type, condition, and age to address our hypotheses (confirmatory analysis), and prime type, condition, and word reading ability (exploratory analysis) on accuracy and reaction times. For each analysis, we examined (a) whether the magnitude of priming (measured through the difference in RTs to related vs. unrelated primes) was greater in the morphological and pseudomorphological conditions compared to the form condition when averaging across age, providing evidence of morphological and morpho-orthographic decompositions respectively (Hypothesis 1), and (b) whether this effect becomes stronger with age or reading ability (Hypothesis 2). We used R (version 4.0.3; R Development Core Team, 2017) and the lme4 package (version 1.1-25; Bates, Maechler, Bolker, & Walker, 2015) to run (generalized) linear mixed-effects models examining the effects of condition (morphological vs. pseudomorphological vs. form), prime type (related vs. unrelated), and age (in months) or word reading ability (raw scores on the Sight Word Efficiency subtest of the TOWRE-2) on log odds of accuracy and RTs.

### 3.1. Confirmatory Analysis by Age

The accuracy data were not used as a direct measure of priming, but are reported for reference because the RT data comprised correct responses only. Condition, prime type, age in months, and the condition × prime type × age in months interaction were entered into the model as fixed effects. In all analyses reported below, ‘prime type’ was centered using deviation coding, and ‘age’ was mean-centered and scaled.

For each analysis, we first identified the maximal random effects structure, incorporating by-participant and by-item random intercepts, along with by-participant random slopes for the effects of condition, prime type, and the condition × prime type interaction, and by-item random slopes for the effects of prime type, age, and the prime type × age interaction (i.e. random slopes for all within-subject and within-item predictors and their interactions; Barr, Levy, Scheepers, & Tily, 2013). In instances where the maximal model failed to converge, modifications were made based on recommendations from Brauer and Curtin (2018) and Matuschek, Kliegl, Vasishth, Baayen, and Bates (2017) until the most complex model supported by the data was identified.

### 3.1.1. Accuracy

Response accuracy for the primed lexical decision task was high across all age groups (see Table 3). One participant in the younger adolescent group scored below 75% accuracy, and was removed from the analysis (following Beyersmann et al., 2012). A further participant from the older adolescent group was excluded due to a software error during the running of the experiment. All other data were included in the analyses. Analysis was based on 20604 observations from 202 participants responding to 102 items.

Table 4 shows the output from the model examining the effects of condition, prime type and age on accuracy. In this model, the form condition is the reference level, represented by the intercept, and all estimates are relative to this baseline. Turning first to the interaction between condition and prime type (averaged across age), the difference in response accuracy to words preceded by related and unrelated primes did not differ between the morphological and form conditions (z = 1.66, p = .097) or the pseudomorphological and form conditions (z = -0.72, p = .472). Examining the three-way interaction between condition, prime type and age shows that, relative to the form condition, response accuracy in the pseudomorphological condition increased more for unrelated vs. related primes in line with age (z = -2.69, p = .007). The same trend was not observed for the morphological condition relative to the form condition (z = -1.48, p = .140).

The influence of age on response accuracy to related vs. unrelated primes in each condition was confirmed using the ‘emtrends’ function in the package emmeans (Lenth, 2018). This function tests whether a continuous predictor (i.e. age) has a different trend depending on a given factor (i.e. prime type). Each row in Table 5 contrasts the trends for age for related vs. unrelated primes in one of the three conditions. A positive estimate indicates that accuracy increases with age for responses to related primes to a greater extent than for unrelated primes; a negative estimate indicates the reverse.

These analyses indicate that in the pseudomorphological condition, response accuracy to words preceded by unrelated primes increased to a greater extent with age than response accuracy to words preceded by

---

**Table 7**

Comparing the effect of age on RTs for related vs. unrelated primes, split by condition

| Outcome | Contrast            | Condition                | Estimate | SE  | z ratio | p value |
|---------|---------------------|--------------------------|----------|-----|---------|---------|
| RTs     | Related - Unrelated | Morphological            | 0.02     | 0.01| 2.40    | .017    |
|         | Related - Unrelated | Pseudomorphological      | 0.02     | 0.01| 2.19    | .028    |
|         | Related - Unrelated | Form                     | 0.00     | 0.01| -0.42   | .673    |

**Table 8**

Generalized linear mixed-effects model output for analysis of condition, prime type and word reading on lexical decision accuracy

| Predictors          | Accuracy | Odds Ratio | SE | z ratio | p value |
|---------------------|----------|------------|----|---------|---------|
| Intercept           |          | 24.43      | 3.75| 20.83   | <.001   |
| Prime_type          |          | 0.86       | 0.11| -1.13   | .257    |
| Word_reading        |          | 1.30       | 0.09| 3.74    | <.001   |
| Condition            |          | 0.93       | 0.19| -0.36   | .717    |
| Condition            |          | 2.16       | 0.48| 3.50    | <.001   |
| Prime_type x Word_reading |    | 0.93       | 0.10| -0.72   | .473    |
| Prime_type          |          | 0.99       | 0.17| -0.07   | .945    |
| Condition            |          | 1.44       | 0.29| 1.84    | .065    |
| Word_reading         |          | 1.08       | 0.08| 1.07    | .286    |
| Condition            |          | 1.04       | 0.09| 0.43    | .667    |
| Prime_type x Word_reading |    | 1.02       | 0.15| 0.15    | .884    |
| Prime_type           |          | 0.91       | 0.16| -0.53   | .597    |

**Note.** The final model was structured as follows: Model ~ glmer (log odds accuracy ~ condition × prime type × word reading + (1 + condition + prime type | participant) + (1 + prime type | item)).

p values less than .05 are indicated in bold.

### 3.1.1. Accuracy

Response accuracy for the primed lexical decision task was high across all age groups (see Table 3). One participant in the younger adolescent group scored below 75% accuracy, and was removed from the analysis (following Beyersmann et al., 2012). A further participant from the older adolescent group was excluded due to a software error during the running of the experiment. All other data were included in the analyses. Analysis was based on 20604 observations from 202 participants responding to 102 items.

Table 4 shows the output from the model examining the effects of condition, prime type and age on accuracy. In this model, the form condition is the reference level, represented by the intercept, and all estimates are relative to this baseline. Turning first to the interaction between condition and prime type (averaged across age), the difference in response accuracy to words preceded by related and unrelated primes did not differ between the morphological and form conditions (z = 1.66, p = .097) or the pseudomorphological and form conditions (z = -0.72, p = .472). Examining the three-way interaction between condition, prime type and age shows that, relative to the form condition, response accuracy in the pseudomorphological condition increased more for unrelated vs. related primes in line with age (z = -2.69, p = .007). The same trend was not observed for the morphological condition relative to the form condition (z = -1.48, p = .140).

The influence of age on response accuracy to related vs. unrelated primes in each condition was confirmed using the ‘emtrends’ function in the package emmeans (Lenth, 2018). This function tests whether a continuous predictor (i.e. age) has a different trend depending on a given factor (i.e. prime type). Each row in Table 5 contrasts the trends for age for related vs. unrelated primes in one of the three conditions. A positive estimate indicates that accuracy increases with age for responses to related primes to a greater extent than for unrelated primes; a negative estimate indicates the reverse.

These analyses indicate that in the pseudomorphological condition, response accuracy to words preceded by unrelated primes increased to a greater extent with age than response accuracy to words preceded by...
related primes, while the same effect was not observed in either the morphological or form conditions (see Table 5).

3.1.2. Reaction times

In addition to the removal of two participants as described above, four individual trials were removed from the analysis due to display timing errors recorded by DMDX. RTs for correct responses were included in the analyses, and inverse transformations were performed on raw RTs to correct for distribution skews. These transformed RTs were used throughout the analyses. Finally, outliers were removed by excluding inverse RTs that exceeded 3.5 standard deviations from individual participant means, amounting to 0.14% of RT data for correct responses. Fig. 1 shows inverted RTs by condition, prime type and age. Note that because RTs in Fig. 1 are inverted, higher values correspond to faster responses. For a summary of untransformed RTs, see Table 3.

Following removal of RTs for incorrect responses and outliers as described above, 19483 observations from 202 participants responding to 102 items were analyzed. Table 6 shows the output from the model used in this analysis, with the form condition as the reference level. Examining first the interaction between condition and prime type, averaged across age, priming in the morphological ($t = 5.64, p < .001$) and pseudomorphological ($t = 2.78, p = .006$) conditions exceeded priming in the form condition. Turning to the three-way interaction between prime type, condition and age, priming in the morphological condition increased significantly with age compared to priming in the form condition ($t = 2.04, p = .042$). The same pattern was marginal for priming in the pseudomorphological condition compared to the form condition ($t = 1.90, p = .057$).

The age-related patterns in priming were again confirmed by comparing whether age had a different trend for related vs. unrelated primes for each condition separately (Table 7). These estimates indicate that the degree of priming increased significantly with age in the morphological and pseudomorphological conditions, but not in the form condition.

3.2. Exploratory Analysis by Reading Ability

A generalized linear mixed effects model was run to examine the effect of word reading ability on accuracy for related vs. unrelated primes, split by condition (Table 9).

![Fig. 2. Plot showing raw inverted reaction time data points, smoothed conditional means and standard error by condition, prime type and word reading ability](image)

For ease of interpretation, raw RTs are reported in Table 3, but note that outlier removal and statistical analyses were based on inverse transformations of raw RTs at the level of individual datapoints. Therefore, means and standard deviations of raw RTs do not correspond exactly to means and standard deviations of inverse RTs.

---

Table 9

| Outcome | Contrast | Condition     | Estimate | SE  | z ratio | p value |
|---------|----------|---------------|----------|-----|---------|---------|
| Accuracy| Related - Unrelated | Morphological | -0.17    | 0.14| -1.21   | .227    |
|         | Related - Unrelated | Pseudomorphological | -0.06    | 0.10| -0.56   | .577    |
|         | Related - Unrelated | Form         | -0.08    | 0.11| -0.72   | .473    |

---

2 For ease of interpretation, raw RTs are reported in Table 3, but note that outlier removal and statistical analyses were based on inverse transformations of raw RTs at the level of individual datapoints. Therefore, means and standard deviations of raw RTs do not correspond exactly to means and standard deviations of inverse RTs.
We focus in these analyses just on the role of word reading ability in same procedure was used to determine the structure of random effects. Confirmatory analysis.

The interaction between condition and prime type is reported in the responses to related vs. unrelated primes in each condition, given that accuracy in response to words preceded by related and unrelated primes did not vary with age in the morphological condition compared to the form condition ($\tau = 0.15$, $p = .884$). Follow up analyses confirmed that, with accuracy as the outcome measure, trends in word reading ability did not differ for related and unrelated primes in any of the three conditions (see Table 9).

### 3.2.2. Reaction times

Fig. 2 shows inverted RTs by condition, prime type and word reading ability. Analysis was based on 19385 observations from 201 participants responding to 102 items. Table 10 shows the output from this model. Coefficients corresponding to the three-way interaction between word reading, condition and prime type indicate that priming in the pseudomorphological condition increased significantly with word reading ability relative to priming in the form condition ($t = 2.07, p = .038$), but the same pattern was not observed for morphological priming ($t = 1.61, p = .108$). This was reflected in the follow up analyses (Table 11), which showed a marginally lower trend towards an increase in priming with word reading ability in the pseudomorphological condition in the absence of such a trend in either the morphological or form conditions.

### 4. Discussion

Our aim was to investigate the mechanisms underpinning morphological decomposition in developing readers, and to examine how these vary in accordance with reading experience. A sample of 202 children and adolescents ranging in age from 9 to 18 years completed a masked prime lexical decision task in response to targets that were preceded by a) morphologically-related primes (teacher – TEACH; morphological condition), b) primes sharing a surface morphological relationship with the target in the absence of semantic overlap (corner – CORN; pseudomorphological condition), and c) primes that overlapped only in form with the target (window – WIND; form condition). Averaging across age and word reading efficiency, we found evidence of morpho-orthographic decomposition, indexed by priming in the pseudomorphological condition, increased with reading experience. We found some evidence that the magnitude of pseudomorphological priming increased with age, although the same pattern was also observed for morphological priming, and there was only weak evidence that this increase was distinct from priming in the form condition. However, our exploratory analysis taking word reading efficiency in place of age indicated an increase in pseudomorphological priming in line with word reading ability that was distinct from form-related priming. The same pattern was not observed in the morphological condition.

We turn first to the overall pattern of priming across the three conditions. Our observation of morphological priming that was distinct from effects of orthographic overlap replicates previous work in both adults (Longtin et al., 2003; Rastle et al., 2004) and children (Beyersmann et al., 2012; Hasenäcker et al., 2016; Quémart et al., 2011, 2017), and supports the theory that readers as young as 9-10 years decompose semantically transparent complex words in the early stages of word recognition. Our finding that priming in the pseudomorphological condition also exceeded form priming when data were collapsed across age provides evidence for a decomposition mechanism based on effects of word reading, condition and prime type, and their three-way interaction, on log odds of accuracy, while a linear mixed effects model was used to examine the effects of the same predictors on inverted RTs. These analyses were run with raw scores on the TOWRE-2 Sight Word Efficiency subtest entered into the models in place of age. One participant did not complete the word reading task and was excluded from the analysis. Predictor variables were coded as before, and the same procedure was used to determine the structure of random effects. We focus in these analyses just on the role of word reading ability in responses to related vs. unrelated primes in each condition, given that the interaction between condition and prime type is reported in the confirmatory analysis.

#### 3.2.1. Accuracy

Analysis was based on 20502 observations from 201 participants responding to 102 items. See Table 8 for the output from this model. Estimated model coefficients for the three-way interaction indicated that accuracy in response to words preceded by related and unrelated primes did not vary with age in the morphological condition compared to the form condition ($z = -0.53$, $p = .597$), or in the pseudomorphological compared to the form condition ($z = 0.15$, $p = .884$). Follow up analyses confirmed that, with accuracy as the outcome measure, trends in word reading ability did not differ for related and unrelated primes in any of the three conditions (see Table 9).

### Table 10

| Predictors | Estimates | SE | t value | p value |
|------------|-----------|----|---------|---------|
| Intercept $^a$ | 1.41 | 0.02 | 62.33 | <0.001 |
| Prime_type | -0.02 | 0.01 | -1.41 | .157 |
| Word_reading | 0.19 | 0.02 | 11.47 | <0.001 |
| Condition_pseudomorphological | -0.00 | 0.02 | -0.03 | .975 |
| Condition_morphological | 0.08 | 0.02 | 3.51 | <0.001 |
| Prime_type x Word_reading | -0.01 | 0.01 | -0.96 | .338 |
| Prime_type x | 0.05 | 0.02 | 2.69 | .007 |
| Condition_pseudomorphological | | | | |
| Prime_type x Condition_morphological | 0.10 | 0.02 | 5.59 | <0.001 |
| Word_reading x | 0.00 | 0.01 | 0.60 | .548 |
| Condition_pseudomorphological | | | | |
| Word_reading x Condition_morphological | 0.01 | 0.01 | 1.00 | .315 |
| Prime_type x Word_reading x | 0.02 | 0.01 | 2.07 | .038 |
| Condition_pseudomorphological | | | | |
| Prime_type x Word_reading x | 0.02 | 0.01 | 1.61 | .108 |
| Condition_morphological | | | | |

Random effects

$\sigma^2$ | 0.11 |
$t00$ Fun | 0.05 |
$t00$ Target | 0.01 |
$t1$ Fun| Prime_type1 | 0.00 |
$t1$ Target| Prime_type1 | 0.00 |
$\beta01$ Fun | 0.03 |
$\beta01$ Target | -0.14 |
$\kappa$ | 0.36 |
$N_{fun}$ | 201 |
$N_{target}$ | 102 |
Observations | 19385 |
Marginal $R^2$ / Conditional $R^2$ | 0.190 / 0.481 |

---

Note. The final model was structured as follows: Model: $\logit$ (RT $\sim$ condition $^a$ prime type $^a$ word reading + (1 + prime type|participant) + (1 + prime type|item)).

$^a$ The intercept represents inverted reaction times in the baseline (form) condition, averaged across word reading score and prime type.

### Table 11

| Outcome | Contrast | Condition | Estimate | SE | z ratio | p value |
|---------|----------|-----------|----------|----|---------|---------|
| RTs | Related - Unrelated | Form | -0.01 | 0.01 | -0.96 | .338 |
| RTs | Related - Unrelated | Pseudomorphological | 0.02 | 0.01 | 1.88 | .060 |
| RTs | Related - Unrelated | Morphological | 0.01 | 0.01 | 1.25 | .211 |

$p$ values less than .05 are indicated in bold.
orthographically-defined morphemic units (morpho-orthographic segmentation; Rastle et al., 2004; Rastle & Davis, 2008). Such a mechanism gives rise to an initial parsing of items with a pseudomorphological structure (e.g., corner), such that decomposition is not limited to words with a true morphological structure (e.g., teacher).

We found some evidence to suggest that these effects increase with age. When examining priming trends by age for each condition separately, the magnitude of both morphological and pseudomorphological priming was stronger for older readers. In particular, the presence of pseudomorphological priming appeared to be driven by the older readers (see Fig. 1 – 175 months corresponds to approximately 14.5 years of age). However, despite the observed age-related trends in priming, the three-way interaction between age, prime type and condition fell short of significance, which suggests that more evidence may be needed to confirm that stronger pseudomorphological priming with age is not the product of more general increases in sensitivity to orthographic overlap. One possibility is that this study was insufficiently powered to test the three-way interaction (Brysbaert, 2019). Post-hoc data simulations using the simr package (Green & MacLeod, 2016) in R indicated that, to detect an effect size equivalent to that observed for the age x prime type x condition (pseudomorphological vs. form) predictor with 80% power and an alpha level of < .05, we would require around 350 participants.

One issue with adopting chronological age as a proxy for reading expertise is that, for older students in particular, reading ability may reflect individual differences in accumulated exposure to words in texts over a number of years, rather than age specifically (Nation, 2017). Therefore, reading proficiency levels of individuals within an academic year group may overlap considerably with both younger and older children. Given the theoretical argument that morpho-orthographic segmentation depends on representations of morphemes at the level of orthography (Grainger & Beyersmann, 2017; Taft, 2006; Xu & Taft, 2015), orthographic knowledge may be a better predictor of morpho-orthographic segmentation than chronological age.

Recent investigations into individual differences in morphological decomposition lend support to this idea. Andrews and Lo (2013) adopted a masked priming paradigm with skilled readers using the same three conditions reported here. They also measured semantic knowledge via a vocabulary task and orthographic knowledge via a combination of two spelling tasks. They found that individuals who presented with stronger semantic knowledge relative to orthographic knowledge showed markedly greater priming in the morphological condition than in the pseudomorphological condition. By contrast, individuals with better orthographic relative to semantic knowledge demonstrated stronger pseudomorphological priming effects coupled with weaker morphological priming effects. Individual differences in reading and language proficiency have also been shown to modulate priming effects using nonword primes in French children (Beyersmann, Grainger, et al., 2015) and adults (Beyersmann, Casalis, et al., 2015) respectively.

As all participants in this study completed an assessment of word reading efficiency as part of the battery of background measures, it was possible to investigate whether there was stronger evidence for morpho-orthographic segmentation in participants with better orthographic knowledge (measured through word reading skill). Our exploratory analysis indicated that the magnitude of pseudomorphological priming increased to a greater extent than form priming in line with reading ability. The same pattern was not observed for morphological priming. This is in line with evidence of morpho-orthographic segmentation, typically observed in skilled adult readers and not children (Beyersmann et al., 2012; Rastle et al., 2004), is stronger in individuals with better word reading skills.

The trends reported above indicate changes in the processes underpinning morphological decomposition. While semantic transparency appears to be the primary factor driving morphological priming in younger or less able readers, once individuals reach a certain level of reading expertise, morphological analysis seems based at least in part on the orthographic properties of morphemes. One question arising from these observations is how this pattern fits with the timecourse of morphological processing identified by Rastle et al. (2000), in which form-based analysis occurs in the earliest stages of word recognition, while morpho-semantic effects emerge later on. Or, to put it another way, if younger readers do not segment complex words on the basis of morpho-orthographic structure, what drives decomposition of semantically transparent morphological items?

One proposal outlined by Grainger and Beyersmann (2017) is that developing readers rely on embedded stem activation (i.e., identifying teach in teacher), a non-morphological process which provides a gateway for the gradual encoding of affixes as morpho-orthographic units in line with reading experience (see also Beyersmann et al., 2019; Beyersmann, Grainger, et al., 2015; Hasenacke et al., 2016). On this view, any embedded stem is activated during processing (i.e. teach, corn and wind are all activated during processing of teacher, corner and window respectively), leading to lateral inhibition arising from lexical competition between prime and target (C. J. Davis & Lupker, 2006; for similar evidence of lexical inhibition in developing readers, see Tamura, Castles, & Nation, 2017). For all readers, feedback from shared morpho-semantic representations for prime-target pairs such as teacher-teach means that inhibition is reduced, resulting in observed priming effects for words sharing a true morphological relationship. Further, activation of teach while processing teacher facilitates the formation of links between the semantic (and syntactic) properties of affixes and their orthographic form. Eventually, as developing readers gain experience of affixes in different lexical contexts, they develop orthographically-defined representations that are activated during word recognition. As a result, priming is additionally observed for pseudomorphological items such as corner in more skilled readers because embedded stem activation (corn) is supplemented by activation of the morpho-orthographic representation of the affix (-er).

By this account, morphological priming in developing readers is dependent on semantic transparency in the relationship between prime and target, and the absence of form-level affix representations means that complex words are not fully decomposed into stem and suffix. The idea that the emergence of morpho-orthographic segmentation is driven by consolidation of affix representations echoes earlier models of morphological processing (e.g., Schreuder & Baayen, 1995), and highlights the critical role of reading experience in linking pre-existing knowledge about the function of affixes, acquired through spoken language exposure, with their orthographic forms.

The association between individual differences in word reading efficiency and morpho-orthographic segmentation resonates with the findings reported by Andrews and Lo (2013), and partially aligns with results reported in Beyersmann, Grainger, et al. (2015), who found that reading proficiency predicted suffixed nonword priming (e.g., tristerie – TRISTE; the equivalent of sadery - SAD), but not suffixed word priming (e.g., tristesse – TRISTE; the equivalent of sadness – SAD) in French children aged 7-11 years. Suffix word nonword priming is similar to pseudomorphological priming in that there is no semantically interpretable relationship between the complex word and its stem, and priming may therefore be evidence of morpho-orthographic segmentation. However, Beyersmann, Grainger, et al. (2015) also found that reading proficiency modulated priming in their nonsuffixed nonword condition (e.g., tristald – TRISTE), the equivalent of form-related pairs (window – WIND) in the present study. This pattern was not observed here, as reading proficiency predicted the extent to which pseudomorphological priming was distinct from form-only priming, and strength of priming in the form condition did not vary with reading ability.

These differences may reflect the distinction between processing of real (e.g., window) and nonword (e.g., tristald, or windald for an English equivalent) nonsuffixed items. According to some accounts of morphological processing (Grainger & Beyersmann, 2017; Taft, 2006; Taft & Nguyen-Hoan, 2010), lexical competition between orthographically-overlapping words (e.g., window – wind) leads to inhibition of the
target. However, nonword items (e.g., *windald*) result in activation of the embedded word (*wind*) in the absence of competition from the whole-word item (*windald*), because it is not a known word. Consequently, the same target may be primed when it is preceded by a form-related nonword, and inhibited when it is preceded by a form-related real word. If sensitivity to the presence of embedded stems increases with reading ability, as argued by Beyersmann, Casalis, et al. (2015), then strength of priming for non suffixed nonword items may be linked to reading proficiency. However, the children comprising the Beyersmann, Grainger, et al. (2015) sample were also comparatively young, ranging from 7 to 11 years. This may have limited the extent to which differential effects of reading proficiency could be observed across conditions. In the present study, Fig. 1 indicates no evidence of pseudomorphological priming until around mid-adolescence, so it is possible that the age and reading ability range included in Beyersmann, Grainger, et al. (2015) was too narrow to capture individual differences in priming across suffixed and nonsuffixed nonword conditions.

More broadly, the links between reading expertise and morpho-orthographic segmentation align with recent insights into the structure of the English writing system and how it supports direct links between orthography and semantics (see Rastle, 2019a). Morphological regularities are more salient in written English than they are in spoken English, and there are numerous examples of complex words in which the stem is preserved in the orthography, but not the phonology (e.g., *magician*). Recently, attention has turned to how spellings of affixes provide strong cues to meaning, and specifically, word class (Berg & Aronoff, 2017; Ulicheva, Harvey, Aronoff, & Rastle, 2020). Ulicheva et al. (2020) showed that the spellings of 154 English suffixes were highly reliable predictors of word class, even when a number of alternate spellings for that particular sound sequence occurred in non-suffix contexts. They argued that the availability of multiple possible grapheme-phoneme mappings in English permits the emergence of strong associations between specific sequences of letters (i.e. suffixes) and their meanings. Importantly, these findings reveal that the links between suffix spellings and word class are more salient than the links between suffix pronunciations and word class. Given that children are sensitive to statistical patterns of co-occurrence in the linguistic input (Seidenberg & MacDonald, 2018), learning to read may accelerate children’s learning of affixes, and in particular the mappings between their orthographic forms and meanings.

For example, the most common pronunciation of the suffix –*ous* is /əʊs/, but this sound sequence also occurs in word-final position in a number of nomorphemic words (e.g., *bonus, focus*; Berg & Aronoff, 2017), some of which also include a pseudostem in their phonological, but not orthographic, form (e.g., *bone, folk*). Therefore, the links between suffix form and meaning are to some extent masked by other items that share the same word-final sound sequence, but do not overlap in meaning. Once children are exposed to the spellings of words containing the –*ous* suffix, regularity in meaning becomes more apparent through a distinction between items ending in /əʊs/ that take the –*ous* spelling and signal an adjective, and non-adjectival items ending in /əʊs/ that take a variety of different spellings (e.g., –*us*). For these reasons, the process of learning to read may foster awareness of more detailed patterns of association between word form and meaning due to the largely unique relationship between suffix spellings and word class (Berg & Aronoff, 2017; Ulicheva et al., 2020).

Sensitivity to these regularities will take time to build, since children need to encounter items of affixes across a sufficient number of items for statistical patterns to emerge. Additionally, texts designed to promote independent reading in younger readers often prioritize regularity in grapheme-phoneme mappings over vocabulary breadth or morphological complexity (for example, decodable texts incorporated into phonics programmes; Solity & Vousden, 2009). However, as reading skills develop, children and adolescents are more likely to encounter words in texts that comprise a broader range of affixes and multiple layers of affixation (Nagy & Anderson, 1984; Nagy, Carlisle, & Goodwin, 2014).

Existing theoretical accounts of morphological processing were developed primarily to account for morphological effects in skilled word recognition (Amenta & Crepaldi, 2012; Baayen, Dijkstra, & Schreuder, 1997; Diependaele, Sandra, & Grainger, 2005; Giraud & Grainger, 2001; Gonnerman et al., 2007; Rastle & Davis, 2008). Less considered is the nature of morphological knowledge that developing readers draw on when processing complex words, and how this changes with experience. Evidence from skilled readers indicates that encountering novel affixes across a diverse range of stems supports learning and generalization of those affixes to new lexical contexts (Tamminen, Davis, & Rastle, 2015) – a finding that may have implications for the acquisition of affix knowledge in children. One developmental account proposes a role for embedded stem activation, a mechanism via which abstract morpho-orthographic representations of bound morphemes (e.g., affixes) emerge over time (Grainger & Beyersmann, 2017). Overall, our findings are consistent with this theory, although from a purely statistical perspective, activation of embedded stems is not a necessary precursor to the detection of affix spelling-meaning regularities, as these regularities arise between complex words sharing similar meanings (e.g., a person who does something) and word-final spelling patterns (e.g., –*er*).

Importantly, the idea that the development of morpho-orthographic processing is driven by reading experience predicts that it will be subject both to individual- and item-level variation. While evidence reported here and elsewhere (e.g., Andrews & Lo, 2013; Beyersmann, Grainger, et al., 2015) indicates that individual differences in language and reading proficiency modulate whether morphological analysis is based on orthographic form during visual word recognition, less is known about the role of item-level characteristics. Complex words vary in their semantic, phonological, and orthographic transparency (Carlisle, 2003). The meaning of *farmer* can be computed from the meanings of its component morphemes, and the spelling and pronunciation of the stem is preserved in its derived form. On the other hand, *listless* is semantically opaque, while *spatial* undergoes both a phonological and orthographic shift from its stem. If children learn about morphology by detecting regularities in the input, then exposure to highly transparent items may facilitate a more rapid learning process than encounters with items that have a more opaque association with their morphological relatives. While effects of orthographic, phonological and semantic transparency have been demonstrated in developing readers in relation to morphological processing (Lázaro, García, & Burani, 2015; Quémart et al., 2017; Quémart & Casalis, 2014), it is less clear how these factors impact on learning.

These differences have implications for acquisition of affix knowledge, because individual affixes differ in both their productivity (Hay & Baayen, 2002; Plag, 2018) and the transparency of the complex words they form (Tyler & Nagy, 1989), depending in part on their etymological origins. Combined with variation in the strength of association between the phonological and orthographic forms of affixes and their meanings (Ulicheva et al., 2020), it is likely that form-based representations of affixes develop at different rates. While these questions are beyond the scope of the current paper, they highlight the need for a comprehensive examination of the interplay between individual- and item-level characteristics in order to pinpoint the factors that drive the development of morpho-orthographic segmentation.

Our aim was to provide a comprehensive picture of how morphological processing evolves across reading development, but capturing morphological effects across such an extensive age range raises some limitations. One challenge of adopting the same stimuli set across all readers is that properties such as word frequency and orthographic neighborhood size (N) depend on language exposure, and their influence on word recognition may not be uniform across reading development (Monaghan, Chang, Welbourne, & Brysbaert, 2017). In this instance, stimuli were selected to be suitable for developing readers (Beyersmann et al., 2012), and frequency and N were high. These factors are known to influence decomposition processes (Forster, Davis, Schoknecht, &
A second potential issue lies with differences in the phonological transparency of items across conditions. In the morphological condition, all items could be considered fully transparent because the pronunciation of the stem was identical whether it appeared in isolation or combined with a suffix. On the other hand, approximately half of the targets in the pseudomorphological (e.g., many – MAN) and form (e.g., hotel – HOT) conditions differed in their pronunciations when they appeared as embedded stems in the prime. However, it is unlikely that this factor accounts for the pattern of findings presented. Data from masked priming studies using prime-target pairs with full phonological overlap reveal weak or no effect in skilled readers, and no effect in developing readers (C. Davis, Castles, & Jakovljevic, 1998; Rastle & Brysbaert, 2006). First, in priming studies examining evidence for morpho-orthographic segmentation in skilled readers, the same pattern of priming has been demonstrated when items are matched on phonological transparency (Whiting, Shtyrov, & Marslen-Wilson, 2014) and when they are not (Rastle et al., 2004). Finally, variation in phonological transparency would not account for observed differences across pseudomorphological and form conditions, as the split between phonologically transparent and opaque items was relatively balanced (19 items of 34 were phonologically transparent in the pseudomorphological condition compared to 20 of 34 in the form condition). Furthermore, post-hoc analysis examining patterns of priming across pseudomorphological and form conditions revealed no differences in the magnitude of priming for phonologically transparent vs. opaque items, and no interaction of these factors with age (all ps > .05).

5. Conclusions

Our aim was to provide a comprehensive overview of morphological processing during a key period of transition to reading expertise. Our findings provide some evidence that decomposition of morphologically complex words is based on analysis at the level of orthography from mid-late adolescence, although word reading efficiency was a more specific predictor of morph-orthographic decomposition. These findings concur with evidence showing that efficiency of morphological processing undergoes a protracted period of development relative to explicit morphological knowledge, and that mid-adolescence represents an important transitional phase (Dawson et al., 2018). It is possible that these effects arise as the visual word recognition system becomes increasingly attuned to morphological regularities in the writing system, based on accumulated exposure to stems and affixes across diverse contexts (Reichele & Perfetti, 2003; Tamminen et al., 2015). This process may be facilitated by close ties between orthographic forms of affixes and their meanings (Berg & Aronoff, 2017; Ulcheva et al., 2020), which could explain why, in skilled readers, analysis of morphological structure is triggered by the orthographic properties of morphemes. In adopting a fine-grained approach to reading development as we have here, we can begin to address the question of how morphology is implicated in the transition from reading via decoding to rapid recognition of words via a direct pathway from spelling to meaning (Rastle, 2019b). Moving forward, it is critical that morphology plays a more prominent role in developmental theories and models of word reading if we are to capture how accumulation of reading experience over time feeds into recognition of morphologically complex words.

Declaration of Competing Interest
None.

Acknowledgements

We would like to thank Elisabeth Beyersmann for sharing the experimental stimuli and scripts used in Beyersmann, Castles, and Coltheart (2012), and the staff, parents and children of participating schools for their support. This research was funded by Royal Holloway, University of London. The second and third authors are supported by the Economic and Social Research Council (grant numbers ES/P001874/1, ES/K008064/1 and ES/K008064/2 respectively).

Appendix A: Experimental stimuli

| Morphological | Pseudomorphological | Form |
|---------------|---------------------|------|
| Prime | Target | Suffix | Prime | Target | Pseudosuffix | Prime | Target |
| walked (r) | WALK | -ed | mission (r) | MISS | -ion | address (r) | ADD |
| smelled (u) | FILL- ed | | longest (a) | SLIM | -y | speaker (u) | FREE |
| filled (r) | | | slimy (r) | | | freeze (r) | |
| lovely (u) | | | easter (u) | east (r) | -er | tender (u) | |
| toaster (r) | TOAST | -er | likely (u) | EAST | -er | single (r) | SING |
| grocery (u) | | | | | | curled (u) | |

(continued on next page)
| Prime       | Target | Suffix | Prime       | Target | Pseudosuffix | Form       | Prime | Target |
|------------|--------|--------|------------|--------|--------------|------------|-------|--------|
| golden (r) | GOLD   | -en    | lady (r)   | LAD    | -y           | AGAIN      |       |        |
| frosty (u) | CRY    | -ing   | eggs (a)   | SHOULD | -er          | THIN       |       |        |
| crying (r) | BAD    | -ly    | fighting (r)| OORN  | -er          | TEA        |       |        |
| posted (u) | DRY    | -ing   | sticky (r) | OFF    | -er          | WIND       |       |        |
| badly (r)  | SHY    | -ly    | younger (r)| SCAR   | -y           | CAR        |       |        |
| liked (u)  | FLY    | -ing   | older (a)  | MAST   | -er          | BEE        |       |        |
| dying (r)  | TEACH  | -er    | prayer (r) | POST   | -er          | SIGH       |       |        |
| weaker (a) | ACT    | -ing   | forest (r)| FOR    | -est         | TWIN       |       |        |
| sewing (a) | MOOD   | -y     | tooth (r)  | LIST   | -en          | CHIN       |       |        |
| aimed (r)  | MAIN   | -ly    | many (r)   | MAN    | -y           | TOO        |       |        |
| boards (u) | FARM   | -er    | metal (r)  | MET    | -al          | BEG        |       |        |
| shily (r)  | LUCK   | -y     | army (r)   | ARM    | -y           | SKI        |       |        |
| mower (u)  | NAME   | -ed    | cats (a)   | PART   | -y           | ARE        |       |        |
| acting (r) | MAP    | -er    | naughty (r)| NAUGHT | -y           | SPIN       |       |        |
| moody (r)  | HARD   | -er    | painter (u)| BELL   | -y           | MEN        |       |        |
| used (u)   | TRY    | -ing   | fasten (r)| FAST   | -en          | CROW       |       |        |
| trying (r) | EAT    | -ing   | nearly (a)| FABR   | -y           | TURN       |       |        |
| eating (a) | SLY    | -ly    | brother (r)| BOTH   | -er          | YELL       |       |        |
| fixed (u)  | LAY    | -er    | widely (a)| NUMB   | -er          | STAR       |       |        |
| layer (r)  | BUSH   | -y     | fluffy (r)| MILL   | -ion         | HOVE       |       |        |
| milky (u)  | CREAM  | -y     | every (r)  | EVERY  | -y           | COME       |       |        |
| creamy (r) | SLOW   | -ly    | lower (a)  | BUS    | -y           | WON        |       |        |
| darker (r) | DEEP   | -ly    | busy (r)   | FACT   | -ory         | PAST       |       |        |
| slowly (u) | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| leader (r) | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| deeply (r) | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| banked (u) | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |
| aimed (r)  | AIM    | -ed    | cheaper (a)| SAND   | -al          | DRAG       |       |        |

Note. r = related prime; u = unrelated prime

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(JUL), 1–12. https://doi.org/10.3389/fpsyg.2012.00232.

Andrews, S., & Lo, S. (2013). Is morphological priming stronger for transparent than opaque words? It depends on individual differences in spelling and vocabulary. *Journal of Memory and Language*, 68(3), 279–296. https://doi.org/10.1016/j.jml.2012.12.001.

Anglin, J. M. (1993). Vocabulary development: a morphological analysis. *Monographs of the Society for Research in Child Development*, 58(10).

Baayen, R. H., Dijkstra, T., & Schreuder, R. (1997). Singulars and Plurals in Dutch: Evidence for a Parallel Dual-Route Model. *Journal of Memory and Language*, 37(3), 94–117. https://doi.org/10.1006/jmla.1997.2099.

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(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001.
Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Ben-Shachar, M., Dougherty, R. F., Deutsch, G. K., & Wandell, B. A. (2011). The development of cortical sensitivity to visual word forms. *Journal of Cognitive Neuroscience, 23*(9), 2387–2399. https://doi.org/10.1162/jocn.2011.21615

Berg, K., & Aronoff, M. (2004). Self-organization in the spelling of English suffixes: the emergence of culture out of anarchy. *Nature, 93*(1), 37–64. https://doi.org/10.1038/fin.2017.000

Beyersmann, E., Casalis, S., Ziegler, J. C., & Grainger, J. (2015). Language proficiency and morpho-orthographic segmentation. *Psychonomic Bulletin & Review, 22*, 1054–1061. https://doi.org/10.3758/s13420-014-0752-9

Beyersmann, E., Castles, A., & Coltheart, M. (2012). Morphological processing during visual word recognition: reading saying readers. Evidence from masked priming. *The Quarterly Journal of Experimental Psychology, 65*(7), 1306–1326. https://doi.org/10.1080/17470218.2012.656661

Beyersmann, E., Grainger, J., Casalis, S., & Ziegler, J. C. (2015). Effects of reading proficiency on embedding priming in primary school children. *Journal of Experimental Child Psychology, 139*, 115–126. https://doi.org/10.1016/j.jecp.2015.06.001

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

Beyersmann, E., Moukissou, P., Javourey-Drevet, L., Schroeder, Z., Ziegler, J. C., & Grainger, J. (2020). Morphological Processing Across Modalities and Languages. *Scientific Studies of Reading, 24*(6), 500–519. https://doi.org/10.1080/10888438.2020.1730470

Brauer, M., & Curtin, J. J. (2018). Linear mixed-effects models and the analysis of nonindependent data: A unified framework to analyze categorical and continuous independent variables in fully within-subjects and/or within-between designs. *Psychological Methods, 23*(3), 389–411. https://doi.org/10.1037/met0000159

Brynska, P., & Nunes, T. (2004). Morphology and Spelling. In T. Nunes & P. Bryant (Eds.), *Handbook of Children’s literacy* (pp. 91–118). Kluwer Academic Publishers.

Bryson, M. (2019). *Participating in the alphabetic code: How do children include in Properly Powered Experiments? A Tutorial of Power Analysis with Reference Tables. Journal of Cognition, 21*(1), 1–38. https://doi.org/10.5334/joc-204

Brysbaert, M., Mandera, P., & Keuleers, E. (2018). The Word Frequency Effect in Word Processing: An Updated Review. *Psychological Bulletin, 144*(3), 301–338. https://doi.org/10.1037/bul0000161

Castles, A., Rastle, K., & Nation, K. (2018). Ending the Reading Wars: Reading Research, 38(4), 291–318. https://doi.org/10.1002/dys.1458

Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal representation of morphology in children. *Journal of Experimental Psychology: Human Perception and Memory, 3* (2), 169–184. https://doi.org/10.1037/0096-1523.3.2.169

Forster, K. I., & Forster, J. C. (2003). *DMDX: A Windows display program with millisecond accuracy*. Behavior Research Methods, Instruments, and Computers, 35(1), 21–124. https://doi.org/10.3758/BF03196500

Grainger, J., & Bueyermann, E. (2017). Edge-Adjusted Embedded Word Activation Initiates Morpho-orthographic Segmentation. In *67. Psychology of Learning and Motivation*. https://doi.org/10.1016/bs.plm.2017.03.009

Green, P., & Macdonell, C. (2016). *SMIR: An R package for power analysis of generalized linear mixed models by simulation*. Methods in Ecology and Evolution, 7(4), 493–498. https://doi.org/10.1111/2041-210X.12504

Harman, M. W., & Seidenberg, M. S. (2004). Computing the Meanings of Words in Reading: Cooperative Division of Labor Between Visual and Phonological Processes. *Psychological Review, 111*, 662–720.

Hasenack, J., Bueyermann, E., & Schroeder, S. (2016). Masked morphological priming in German-speaking adults and children: Evidence from response time distributions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*(6), 1345–1355. https://doi.org/10.1037/xlm0000500

Hay, J., & Baayen, H. (2002). Parsing and productivity. In G. Boosy, & J. Van Marle (Eds.), *Yearbook of Morphology 2001* (pp. 203–235). Springer.

Kirby, J. R., Deacon, S. H., Bowers, P. N., Issenberg, L., Wade-woolley, L., & Pallara, R. (2012). Children’s morphological awareness and reading ability. *Reading and Writing, 25*(2), 389–410. https://doi.org/10.1007/s11145-010-9276-5

Kruis, R. S., & Bergman, K. (2013). The reciprocal relations between morphological processes and reading. *Journal of Experimental Child Psychology, 114*(1), 10–34. https://doi.org/10.1016/j.jecp.2012.09.014

Lazarro, M., Camacho, L., & Burzani, C. (2013). Morphological processing in reading disabled and skilled spanish children. *Dyslexia, 19*(3), 178–188. https://doi.org/10.1002/dys.1408

Lazarro, M., Garcia, L., & Burzani, C. (2015). How orthographic transparency affects morphological processing in young readers with and without reading disability. *Scandinavian Journal of Psychology, 56*(5), 498–507. https://doi.org/10.1111/sjop.12213

Lazarro, M., Illera, V., Acha, J., Escalonilla, A., García, S., & Sainz, J. S. (2018). Morphological effects in word identification: tracking the developmental trajectory of derivational morphology in children. *Routledge*. https://www.researchgate.net/publication/324805275_The_acquisition_of_derivational_morphology_in_children.

Longtin, C. M., Segui, J., & Hallazgo, G. (2017). Morphological priming and ERPs dissociate maturation of orthographic and semantic components of visual word recognition in children. *Psychophysiology, 54*(2), 136–141. https://doi.org/10.1111/psyp.12834

McCabe, S. F., Brysbaert, M., Keuleers, E., & Rastle, K. (2009). Is morphological decomposition limited to low frequency words? The *Quarterly Journal of Experimental Psychology, 62*(10), 1706–1715. https://doi.org/10.1080/1747021090289991.
