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Breadmore, Helen; Côté, Emily; Deacon, Helene

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The Timing Tells the Tale: Multiple Morphological Processes in Children's and Adults' Spelling

Helen L. Breadmore [a], Emily Côté [b], and S. Hélène Deacon [b]

[a]Centre for Global Learning, Coventry University, Coventry, UK; [b]Department of Psychology and Neuroscience, Dalhousie University, Halifax, Canada

ABSTRACT

Purpose: Despite abundant evidence that morphemes are important in reading and spelling, little is known about the nature of processing in spelling. This study identifies multiple morphological processes over the time course of spelling, revealing that these processes are influenced by development.
Method: Twenty adults and 46 children (8;0–12;1 years) completed an auditory lexical decision task followed by a spelling task, to explore the effects of morphological structure and cross-modal morphological priming by analyzing handwriting latencies before and during spelling production.
Results: Adults and children both demonstrated morphological processing during lexical access – they were faster to begin to write morphologically complex words (e.g., artist) compared to matched monomorphemic controls (e.g., article). Adults (but not children) also demonstrated cross-modal morphological priming. Further, adults (but not children) demonstrated the effects of morphological processing during spelling production. Inter-letter latencies were shorter between the last two letters of a root morpheme than the same letters in monomorphemic control words (e.g., ar[]tist compared to ar[]ticle).
Conclusion: Together, these findings reflect multiple facilitative effects of morphological processing during spelling production – during lexical access and spelling production. This highlights the need for greater integration of morphological processes into theories of skilled spelling and spelling development.

There is abundant evidence that children use morphemes, the smallest meaningful units of language, to spell words accurately (e.g., *turn* and *-ing* in *turning*, Angelelli et al., 2014; Deacon & Bryant, 2006b; Deacon et al., 2008; Fejzo, 2016; Treiman & Cassar, 1996). However, it is not yet clear *when* morphemes are activated during the spelling process. According to models of skilled spelling, the speller first accesses their lexical representation and then holds this representation in working memory while physically producing the spelling (Bonin et al., 2015; Côté et al., in press; Levesque et al., 2021; Olive, 2014). Morphological processing could take place at any stage of this process, yet neither empirical research nor theories of spelling have adequately explored the question of when morphemes influence spelling. This is the question explored here; does morphological processing only occur during lexical access, or is morphological information also used during the production of spellings? This is of theoretical importance because it asks *how* and *why* morphemes influence spelling. The answer may change over development and determining whether this is the case has educational implications, in addition to refining theory.

CONTACT Helen L. Breadmore h.breadmore@bham.ac.uk School of Education, University of Birmingham, Edgbaston, Birmingham, West Midlands B15 2TT, UK
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The question of when morphemes influence spelling processes draws directly on current models of skilled word writing, which highlight three stages of the spelling process; input identification, central orthographic, and peripheral orthographic processes (Bonin et al., 2015; Côté et al., in press; Olive, 2014). Input identification takes the speller from the stimulus to lexical representation. These processes vary depending on the nature of the input (e.g., spelling-to-dictation, copying, ideation). Once the lexical representation is accessed, central orthographic processes are activated, translating the word into letter representations and organizing them into sublexical units which can be held in working memory during spelling production. Peripheral orthographic processes translate those units into the motor responses needed to execute production of the word – pen movements for handwritten spellings. Henceforth, we distinguish between processes that occur during lexical access (input identification) from those during spelling production (central orthographic processing), respectively, bringing our terminology in line with that used in reading and spoken word recognition literature. Morphological information could influence input identification during lexical access, central orthographic processing during spelling production, or both processes.

Developmental models of spelling are virtually silent about when morphological processing occurs during spelling production. Instead, these models have focused on when, over the course of development, children begin to use morphological information to guide spelling (Deacon & Sparks, 2015 review). Some argue that young children's spelling is initially dominated by phoneme-grapheme correspondence, with attention to morphemes occurring later, around 8 years of age (Ehri, 1995, 2005; Gentry, 1982). Others argue that even young children's spellings are influenced by morphological features (Deacon et al., 2008; Treiman, 2017). However, morphemes are multidimensional – they carry phonemic, graphemic, semantic and grammatical information. Each aspect might influence different spelling processes. For example, morphological information may influence lexical access due to its role in lexical organization, and/or morphemes might be useful sublexical graphemic units to hold in working memory during spelling production. If morphemes have multiple influences on spelling, these different processes might not all develop simultaneously.

This idea resonates with the recent Morphological Pathways Framework which describes multiple morphological processes distributed through linguistic and writing system knowledge as well as within lexical representations (Levesque et al., 2021). Although the Morphological Pathways Framework is applied to both reading and spelling, it is heavily grounded in evidence from reading. Here, we tackle this evidence gap by exploring morphological processing at different stages of the spelling process – during lexical access and during spelling production. To understand how morphology influences spelling, we need to distinguish the effects of processes that occur during these stages of production. Could the facilitatory effects of morphological structure previously documented in spelling accuracy (Deacon et al., 2008 review) originate solely from morphological processing during lexical access? Do additional morphological processes occur during spelling production (Côté et al., in press; Gagné & Spalding, 2014; Weingerten et al., 2004)? Delineating these component processes is important, not only to improve our theoretical understanding of spelling but also because of the educational implications. If morphological processing occurs during spelling production, then children may benefit from learning spelling-specific morphological strategies. If morphological processes occur during lexical access, then instruction might focus instead on the morphological relations between word meanings (Bowers et al., 2010).

To address the question of when and how morphological information influences spelling we can measure the time taken to begin writing to explore what happens before spelling commenced, and we can examine letter writing durations to explore what happened during spelling. Another way to address this question is to apply established priming techniques from the word recognition literature to the domain of spelling and explore the impact on handwriting latencies. Here, we apply both approaches to study age-related changes in morphological processing, before and during spelling production.

Morphological processing during lexical access: input identification

There is plentiful evidence that morphological processing occurs during lexical access in reading. A vast literature evidences effects of morphological structure during auditory and visual word recognition and word naming. Morphologically related primes (e.g., *joy* as a prime for *joyful*) facilitate lexical decisions beyond the effects of shared meaning and shared form (Feldman, 2000; Rastle et al., 2000). These priming effects have been demonstrated in adults and children in multiple languages (Beyersmann et al., 2011; Casalis et al., 2009; McCutchen et al., 2009; Quémart et al., 2011). Cross-modal effects are also established for both adults and children – spoken primes facilitate morphologically related visual lexical decisions (Clahsen & Fleischhauer, 2014; Quémart et al., 2017). Collectively, these findings demonstrate the important role of morphological processing during lexical access in reading.

There is limited evidence of morphological processing during lexical access in spelling. Studies using fragment completion tasks have demonstrated that children use morphological processing during lexical access. Participants are provided with a written word with several letters deleted and replaced with underlined blanks (e.g., *need* becomes *ne*_ _) and are asked to write what word comes to mind. In these tasks, morphologically related primes presented simultaneously in both visual and auditory modalities facilitate subsequent fragment completion (Feldman et al., 2002; Rabin & Deacon, 2008).

Very few studies have explored priming effects in spelling, but there is some evidence that morphological priming improves children's spelling accuracy (Rosa & Nunes, 2008). This supports the idea that morphological effects can originate from lexical access. Another possibility is that morphemes are useful sublexical units which can be held in working memory during spelling production. Studying the time course of morphological processing during spelling is therefore essential to understanding whether morphological knowledge merely facilitates lexical access or also facilitates spelling production after the target lexeme has been accessed. Here, we use cross-modal long lag priming (primes presented aurally prior to visual word recognition) to increase the likelihood that these effects reflect lexical rather than orthographic processes and to limit confounding effects of reading ability.

Little is known about the time course of morphological processing during the production of written words, which limits our understanding of the cognitive processes involved in spelling. Latencies before handwriting begins suggest that morphological processing has a facilitative effect on lexical access in spelling (Afonso & Alvarez, 2019; Breadmore & Deacon, 2019; Hess et al., 2021; Quémart & Lambert, 2019). Breadmore and Deacon (2019) showed that English children aged six to 11 years demonstrated shorter writing onset latencies for two- than one-morpheme words (e.g., *rocking* versus *rocket*). A study of German children aged seven to 10 years found longer writing onset latencies when copying words with letters presented in different colors on either side of the morpheme boundary compared to those without this visual disruption (Hess et al., 2021). Spanish adults demonstrate shorter writing onset latencies for compound words than noncompounds (Afonso & Alvarez, 2019). Quémart and Lambert (2019) also found that French adult's writing onset latencies were shorter for two-morpheme words, but this effect was not significant for 10- and 12-year-old children. This contrasts with findings for younger English (6- to 7-year olds in Breadmore & Deacon, 2019) and German children (7- to 10-year olds in Hess et al., 2021). Whereas all root letters were matched in the English and German studies, the French study matched the identity of the letters at either side of the morpheme boundary (e.g., *m* and *i* in ***ferm[.]i****er-che****m[]i****se*, here and henceforth the period indicates the morpheme boundary) but not letters at the beginning of words. Nonetheless, all handwriting studies demonstrate facilitative effects of morphological processing during lexical access. This facilitation is consistent with well-established evidence during visual and auditory word recognition (e.g., Feldman, 2000; Rastle et al., 2000).

In contrast, studies of typing latencies have not typically found facilitative effects of morphological processing in writing onset latencies (Bertram et al., 2015; Gagné & Spalding, 2016b). Nonetheless, these studies still demonstrate effects of morphological processing during lexical access, such as semantic priming effects on keystroke latencies at morpheme boundaries (Gagné & Spalding, 2014).

Morphological processing after lexical access: during spelling production

A few studies have investigated whether morphological processing occurs *during* handwritten spelling production but with inconsistent results (Breadmore & Deacon, 2019; Kandel et al., 2008, 2012; Quémart & Lambert, 2019). In the only study to examine evidence of morphological processing during handwritten spelling in English, Breadmore and Deacon (2019) explored effects on children's root writing time – the time from when the pen touched the paper until it was lifted after the last letter of the root morpheme (or the equivalent letter in one-morpheme words – *rock* in ***rock**.ing* and ***rock**et*). No effects of morphological processing were observed during spelling production, in either age group of children. It could therefore be that morphological processing only influences lexical access but not spelling production. On the other hand, effects during spelling production might have been absent because of the young age of the participants or because of a lack of sensitivity in the metric capturing writing times.

Studies of morphological processing during handwritten spelling have varied in the measures used to explore the time course of processing. In the example above, Breadmore and Deacon (2019) studied large units – the time taken to write the whole word or the root segment of the word. These coarse-grained measures of writing duration can only tell us if, overall, a participant writes a whole section faster, slower, or similarly to a matched segment of another word. These measures are not precise enough to detect *when* changes in speed occur within those segments. Coarse-grained measures may obscure subtle changes in speed, for example, a series of increases and decreases within the segment. Fine-grained metrics such as letter writing duration and inter-letter latencies (i.e., the duration of the pause between two letters) can capture that.

Several studies have used fine-grained metrics to study morphological processing during typed copying. Adults' typing speed changes around morpheme boundaries – keystroke latencies are faster for the last letter of the first morpheme, and then slower for the first letter of the second morpheme (Bertram et al., 2015; Gagné & Spalding, 2014, 2016a, 2016b; Libben & Weber, 2014). This suggests that morphological processing continues to occur during spelling. Handwriting latencies offer further fine-grained analyses compared to typing, as we can distinguish pen movements from inter-letter pauses.

A limited set of studies have used fine-grained metrics to study morphological processing during handwritten copying (Afonso & Alvarez, 2019; Kandel et al., 2008, 2012; Quémart & Lambert, 2019), but with little consensus about when processing occurs. Kandel et al. (2008) found that French university students demonstrated evidence of morphological processing during copying, with longer inter-letter latencies at the boundary between two morphemes than between the same letters in one-morpheme words (i.e. the pause [] between *l* and *e* was longer in two-morpheme *boul[.]ette* than one-morpheme *goél[]ette).* Writing onset latencies were longer in two-morpheme words, but the reliability of this finding is limited because the letters at the beginning of the words were not matched. In a later study with similar methods and sample, longer inter-letter latencies did not reach statistical significance ($p = .07$, Kandel et al., 2012), but the letter before the boundary was not matched. Hess et al. (2021) investigated letter writing duration on the first letter of the second morpheme (e.g., *e* in *golf.**e**r*) in German, when the same words were presented with a visual disruption at the boundary versus no disruption. No evidence of morphological processing was found. Overall, these studies offer little evidence of morphological processing during spelling but confounding factors cloud interpretation.

To our knowledge, only two studies explored the time course of morphological processing across morpheme boundaries during handwriting. In both cases, the identity of letters at either side of the morpheme boundary in two-morpheme words and the equivalent bigram in one-morpheme words were controlled (e.g., *ti* in *ar**t[.]i**st-ar**t[]i**cle*). This enables inspection of morphological processing immediately before and after the boundary using fine-grained writing latencies (i.e., letter writing times and inter-letter latency). Afonso and Alvarez (2019) examined adults' latencies around the morpheme boundary in Spanish compound and non-compound words (e.g., *toc[]**a**[.]**d**iscos – pas[]**a**[] **d**umbre*). Inter-letter latencies were shorter within compound words (in the first constituent), and this was influenced by the frequency of the second constituent. Hence, morphological processing had a facilitatory effect during handwriting production. Quémart and Lambert (2019) revealed developmental differences in morphological processing during spelling production in French (e.g., comparing *mi* in *fer**m**[.]**i**er-che**m**[]**i**se*). Both 12-year olds and adults (but not 10-year olds) had longer letter writing times on the first letter of the matched bigram when it occurred in two-morpheme words compared to one-morpheme words. This suggests that younger children might not use morphological processing during spelling production, but older children and adults do – reflecting the developmental progression of these processes.

In summary, the few available studies on the time course of morphological processing in spelling have inconsistent findings, which could be due to varied methodologies, metrics, and populations of interest. Nonetheless, these studies suggest that handwritten spelling latencies can provide useful information to delineate effects of morphological processing before and during spelling production.

The current study

This study aims to delineate effects of morphological processing that occur during lexical access in input identification, from those that occur during spelling production. We examine the time course of morphological effects during spelling a visually presented stimulus, removed from view during spelling production to ensure lexical access occurs. This paradigm which more closely resembles an authentic writing task compared to a straightforward copy task. We capture coarse-grained and fine-grained measures of latencies before and during spelling, using two methods to induce morphological processing: manipulation of word forms and cross-modal priming. We explore developmental differences by comparing adults and children and exploring the effect of age within child participants.

There is strong evidence that morphological processing facilitates lexical access. In this study, we hypothesize that morphological processing during lexical access will result in an effect of word structure on spelling accuracy and in the latencies before spelling begins. Consistent with previous evidence, we predict that accuracy will be higher and time to begin writing will be faster for two-morpheme derived words (e.g., *sing.er*) compared to matched one-morpheme control words (e.g., *single*). Prior research has only examined coarse-grained latencies before writing begins. Here, we include novel fine-grained measures to separate effects of lexical access (word access duration, equivalent to word reading time) from those of writing onset latency after lexical access.

As another window into morphological processing during lexical access, we examine the effects of cross-modal long lag morphological priming on spelling accuracy and latencies before spelling. This was inspired by extensive evidence from cross-modal priming of lexical decisions (Clahsen & Fleischhauer, 2014; Quémart et al., 2017) and fragment completion (Feldman et al., 2002; Rabin & Deacon, 2008), but no previous evidence from spelling. We hypothesize that auditory primes will facilitate spelling of morphologically related words (e.g., sing-*sing.er*) but will inhibit spelling of matched one-morpheme words (e.g., sing-*single*). That is, morphological priming will increase accuracy and reduce time to begin writing. Meanwhile, for matched one-morpheme words, accuracy will decrease and time to begin writing will increase. Hence, an interaction between priming and word structure reflects morphological processing during lexical access.

Although we anticipate that morphological processing will also affect processes during spelling production, there is insufficient evidence to make strong hypotheses about the location of these effects. Hence, we conduct exploratory analyses of the effects on coarse- and fine-grained latencies during writing; comprehensively exploring the effects of priming and word structure on root writing time, letter writing time on the last letter of the root morpheme (or equivalent in one-morpheme control words) and inter-letter latencies before that letter (e.g., *sin[]**g**.er, sin[]**g**le*). If morphemes are used to hold the letters in memory during spelling production, then we might expect to observe decreased handwriting latencies (faster writing) within morphemes. Shorter inter-letter latencies and letter writing times within a root morpheme could reflect these letters being held together in working memory, within a sublexical unit. Hence, a main effect of word structure on latencies during spelling reflects morphological processing.

Method

Experimental design and procedures were the same for adults and children. Participants completed an auditory lexical decision priming task, the Detailed Assessment of Speed of Handwriting (DASH - Barnett et al., 2007), the spelling task, and the Test of Word Reading Efficiency (TOWRE-2 - Torgerson et al., 2012). Ethical review and approval was conducted by Dalhousie University Social Sciences and Humanities Research Ethics Board which followed the Government of Canada Tri-Council Policy Statement 2 (TCPS2, 2018), as well as Coventry University Ethics Committee. Written informed consent was obtained from parents and oral assent from children before inclusion in the study.

Participants

All participants were typically developing English speakers with normal or corrected-to-normal vision. Twenty adult volunteers (16 females, 4 males) were recruited from the Experimental Participation System (SONA) at a university in Eastern Canada and received course credit as compensation. Fifty-one child participants (8- to 12-year old, Grades 3–5) were recruited from English-only instruction private schools in Eastern Canada, through word-of-mouth, or via a lab-based recontact list to participate. Written consent was obtained from parents and oral consent obtained from children prior to participation. Children were given their choice of small reward (i.e., a sticker, pencil, or eraser) as compensation. Data for five children were removed because they had very low performance on the TOWRE-2 (standardized scores below 70) and struggled to write words – children at the beginning of literacy development were unable to produce sufficient data for inclusion. Hence, data were analyzed for 46 children (21 females, 25 males). Background information is summarized in Table 1.

Design and stimuli

The experimental tasks consisted of an auditory lexical decision task and a spelling task. The auditory lexical decision task included eight items designed to act as primes for the spelling task.

Auditory lexical decision priming task

All 32 words and nonwords were monomorphemic, monosyllabic and matched for length, neighborhood size and bigram frequency. Eight words acted as root primes for the spelling task. Eight were

Table 1. Summary and background information about adults and children.

	Adults		Children	
	Mean (SD)	Range	Mean (SD)	Range
Number of participants	20		46	
Age (years; months)	20;9 (2;12)	18;2–32;3	9;8 (0;12)	8;0–12;1
Standard scores				
TOWRE-2 Sight Word Efficiency	103.50 (13.95)	76–127	98.11 (13.25)	77–126
TOWRE-2 Phonemic Decoding Efficiency	104.85 (5.55)	94–118	92.57 (16.05)	65–126
TOWRE-2 total word reading efficiency	104.35 (8.36)	87–119	95.13 (14.83)	73–120
DASH copy best N words per minute	29.38 (4.63)	21.50–36.50	11.74 (4.48)	4.50–24.50
DASH alphabet writing N letters	91.30 (13.78)	68–115	39.48 (13.02)	14–69
DASH copy fast N words per minute	36.08 (4.67)	29–44	15.47 (5.28)	6.50–26.50
Auditory lexical decision overall accuracy	0.95 (0.08)	0.66–1	0.91 (0.07)	0.66–1

unrelated fillers (unrelated in form and meaning to any other root, derived or control words). Two lists of primes were created and counterbalanced between participants, ensuring that all spelling items occurred in both primed and unprimed conditions between participants. Independent *t*-tests confirmed that primes and fillers were matched for CELEX overall frequency and written frequency, number of letters, phonemes, orthographic and phonological neighbors, bigram token and type frequency (*p*s > .64) (from Davis, 2005). Sixteen nonwords selected from Quémart et al. (2017) were matched to both primes and fillers. Independent samples *t*-tests confirmed that they were well matched for number of letters, orthographic neighbors ($p > .98$), bigram token and type frequency (*p*s > .39). See supplementary files for descriptive statistics (Table S1) and stimuli.

Spelling task

The spelling task had a 2 × 2 within-subjects design. Participants spelled 16 two-morpheme derived words and 16 paired one-morpheme control words beginning with the same letters (selected from Deacon & Dhooge, 2010). These formed the within-subjects variable word structure (derived, control). Half of these words were primed in the auditory lexical decision task, half were not, forming the within-subjects variable priming (primed, unprimed).

The items are presented in supplementary files. Paired samples *t*-tests confirmed that derived and control words were matched for number of letters, phonemes, syllables, neighbors, bigram type and token frequency (Davis, 2005) and the frequency of the bigram on the morpheme boundary between the root and the rest of the word (Jones & Mewhort, 2004).[1] Derived and control words were also matched for frequency on a range of Zeno and CELEX frequencies (Baayen et al., 1995; Zeno, 1995).[2] Three of the root words ended in double letters (therefore the same for derived and control words), and double letters never occurred over the morpheme boundary. Descriptive statistics are presented in supplementary files (Table S2).

Procedure

First, participants completed an auditory lexical decision priming task, followed by the DASH (Barnett et al., 2007), the spelling task and finally TOWRE-2 (Torgerson et al., 2012). In total, this took approximately 30 minutes to complete. Standardized measures of handwriting speed (DASH) and word reading efficiency (TOWRE-2) were administered in line with the manual.

For TOWRE-2, participants first read as many words as possible of increasing difficulty in 45 seconds, providing a measure of word reading efficiency. They then read as many nonwords as possible in 45 seconds, providing a measure of phonemic decoding efficiency. This test yields standardized scores subtest and combined scores for examinees aged 6–24 years old. Audio recordings were scored by a second scorer to ensure inter-rater reliability, which was excellent ($\alpha = .99$).

For the DASH, participants completed three subtests; Copy Best, Alphabet Writing and Copy Fast. Tasks were delivered on a piece of paper overlaid on the graphics tablet to align to and familiarize participants with the experimental task. In Copy Best participants copy a sentence containing every letter of the alphabet as many times as they can in 2 minutes using best handwriting. In Alphabet Writing, participants write the alphabet as quickly as they can for 1 minute. Copy Fast is the same as Copy Best, except participants are asked to copy as quickly as they can. Subtests have high internal consistency with $\alpha > .84$ for all age groups of standardization.

Auditory lexical decision priming task

The experiment was delivered (and data collected) using E-Prime 3.0 on a Toshiba Satellite Pro R850-19 H or Toshiba Satellite Pro C50-A-1E6. Participants listened to audio recordings of the primes, fillers and nonwords and made lexical decisions for each item (32 lexical decisions). A native Eastern Canadian English female speaker recorded word/nonword stimuli (the second author). Stimuli were noise reduced, normalized and trimmed and presented over headphones at a comfortable volume (adjusted for each participant). Left and right index fingers gave responses; “Z” for nonwords and “M” for words. A visual reminder of which keys to use was on the screen throughout, and participants received positive visual feedback after every trial (regardless of performance). Participants were taught which button to press and completed two practice trials, with feedback from the experimenter (*cat*, *wug*) prior to experimental trials. Trial order was randomized for each participant.

Spelling task

The spelling task commenced with a familiarization phase and two practice trials. During familiarization, participants were asked to write using lower-case letters, and to avoid using joined-up letters. They then completed the DASH, the experimenter modeled one practice trial (writing the word *start*) and the participant completed two further practice trials (*cat, snow*) before the experimental trials.

All writing tasks were administered (and data collected) using Eye and Pen 2 software (Alamargot et al., 2006). Responses were given using a ball point nib in a Wacom Intuos 4 InkingPen onto a piece of Letter sized paper overlaid on a medium-sized Wacom Intuos Pro Paper Edition tablet and held in place with a Wacom Paperclip. The tablet was connected to a Toshiba Satellite Pro R850-19 H or Toshiba Satellite Pro C50-A-1E6. This methodology ensured that the writing experience was ecologically valid while responses were simultaneously digitized.

The procedure for practice and experimental trials was identical. Participants controlled trial initiation by tapping the pen on a numbered gray box presented on the paper in line with where they would write the spelling. This pen tap triggered the following sequence of events; an auditory signal, 10 ms delay, commencement of handwriting recording and display of stimulus word on laptop display (in lower case black 18pt Monaco font on a white background, screen resolution 1024 × 768). When participants felt they knew what to write, they tapped the pen on the paper in a white box presented immediately adjacent to where they would write their spelling. This pen tap triggered an auditory signal and removed the target word from the display, ensuring that participants had to read and then retrieve the target from memory. Participants then spelled the word. After writing each word, a final pen tap on a gray box at the end of the line stopped handwriting recording and ended the trial. Participants also received audio feedback to confirm the trial had ended. See Figure 1 for a visual representation of a trial.

Experimental responses were written eight words per page. Trial order ensured that no two words containing the same root were presented on the same page. The position of derived and control, primed and unprimed words was counterbalanced. Half of the primed derived words occurred before

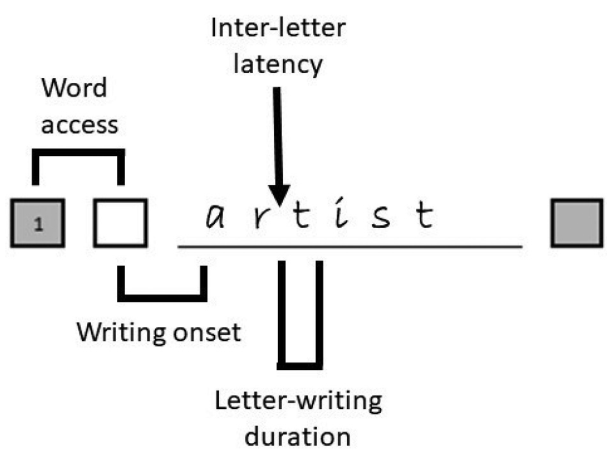

Figure 1. Fine-grained dependent variables for analyses of handwriting latencies. Word access duration is the amount of time from when the word was presented on the screen until participants indicated that they knew what the word was. Writing onset duration is the time from this point until writing began. Inter-letter latency is the time between two letters.Letter-writing duration was measured on the last letter of the root.

the paired controls (and vice versa), and half of the unprimed derived words occurred before the paired controls (and vice versa). Two versions of the auditory priming task were used and counterbalanced between participants to ensure that each word occurred in both primed and unprimed conditions between participants.

Results

Responses to the spelling task were first scored for accuracy. Coarse-grained and fine-grained handwriting latencies were extracted for correct responses only.

Accuracy

Accuracy of spelling is summarized in Table 2. From this, adults' accuracy is clearly at ceiling. Because of the extremely high accuracy and lack of variance, data for adults were not included in further accuracy analyses. A two-way ANOVA was conducted on the dataset from child participants, with the repeated-measures factors priming (unprimed, primed) and structure (control, derived) and the dependent variable accuracy (percentage correct). This indicated that the two-way interaction between priming and structure was not significant, priming*structure $F(1,45) = 0.00$, $p = 1.00$, $\eta_p^2 = .00$. There was a significant main effect of structure, $F(1,45) = 9.08$, $p = .004$, $\eta_p^2 = .17$ but not priming, $F(1,45) = 0.10$, $p = .75$, $\eta_p^2 = .00$. For children, spelling accuracy was significantly higher for derived words compared to controls.

Handwriting latencies

Correct responses were subjected to handwriting analysis with the word segmentation tool in Eye and Pen 2 software (Alamargot et al., 2006). Two coarse-grained dependent variables (total time to begin writing and root writing time) were extracted to explore the time course of effects before and during writing (as Breadmore & Deacon, 2019). Additionally, four fine-grained dependent variables were extracted. Figure 1 illustrates these fine-grained dependent variables.

The dependent variables used to explore the processes taking place during lexical access were total time to begin writing (coarse), word access and writing onset latency (fine). Here, word access latency is the time from the display of the word until the participant tapped the pen on the page to indicate that they were ready to write their response (and the target word was removed from display). Writing onset latency is the time from removal of the target word from the display until the pen touched the paper again to begin spelling. Total time to begin writing is the sum of word access and writing onset latency.

The dependent variables used to explore processes taking place during spelling were root writing time (coarse-grained), letter-writing duration for the final letter of the root, and inter-letter latencies before that letter (fine-grained). Root writing time is the total time from when the pen touched the paper to begin spelling, until it was lifted at the end of the root (or equivalent) part of the word. This

Table 2. Mean (SD) spelling accuracy (percentage correct) for adults and children.

	Adults	Children
Unprimed control	98.75 (3.85)	72.28 (26.21)
Unprimed derived	98.75 (3.85)	79.08 (21.42)
Primed control	98.75 (3.85)	72.83 (24.05)
Primed derived	100.00 (0.00)	78.53 (22.62)
Unprimed	98.75 (2.56)	75.68 (22.25)
Primed	99.38 (1.92)	75.68 (21.38)
Control	98.75 (2.56)	72.55 (23.84)
Derived	99.38 (1.92)	78.80 (19.65)

sums all letter-writing durations and inter-letter latencies to this point. To enable fine-grained analyses of the time course of changes in writing speed, letter-writing duration includes all strokes and inter-letter latencies while writing the last letter in the root morpheme. Inter-letter latency before the last letter of the root is defined as the pause between the last two letters of the root (or equivalent location in control words).

Handwriting latency data were analyzed using linear mixed-effects (LME) modeling with maximum likelihood using the lme4 package (Bates et al., 2014 Version 1.1.27.1) in RStudio (RStudio Team, 2019 version 1.2.5033 running R version 3.6.2). Within each factor, conditions were ordered as indicated within parentheses – the first condition reflects the baseline. The fixed effect of age group (adult, children) was a between-subjects variable. The fixed effects of priming (unprimed, primed) and structure (control, derived) were within-subjects variables. For all models, we first established the maximal random effects structure that achieved convergence and then added fixed effects (Meteyard & Davies, 2020). Accordingly, models initially included (i) random intercepts for participants and items and random slopes for (ii) within-subjects effects and (iii) within-subjects interactions (Barr et al., 2013; Brauer & Curtin, 2018). Statistical significance was ascertained using likelihood ratio tests to compare full and null models. Significance of interactions was tested by comparing the fully specified model to one with additive main effects. Significance of main effects was tested by comparing the model with additive main effects to the null model without the target main effect. If models failed to converge, we removed random slopes until convergence was achieved. This is detailed in text and table footnotes.

In addition to making contrasts between adult and child participants, we explored evidence of developmental effects among the child participants by including age as an additional continuous variable. To allow models to fit, age was centered in these analyses.

For behavioral reasons, 2.7% of adult's, 13.0% of children's data were excluded from the latency analyses (17/634, 145/1114 trials respectively), most commonly because participants joined letters during production of the word. False starts (beginning to write before tapping the white box) and self-corrections (letters produced in the wrong order or crossed out) also contributed to data loss. Because we are interested in examining effects both before and during writing, responses were coded only if all dependent variables could be extracted for that item. Data were checked for normality, and outliers (±3SDs from the participant group mean) removed. After cleaning, data were screened to ensure that each participant contributed at least one data point per condition. Two children were removed from latency analyses because they contributed insufficient data. Following these procedures, 1573 item-level responses contributed to the analyses.

Latencies before spelling begins – during lexical access

First, we examined latencies before spelling began – the coarse-grained measure of total time to begin writing and fine-grained measures of word access duration and writing onset latency. Panels A, B and C in Figures 2 and 3 illustrate overall means by participants. Model fit statistics are presented in supplementary files (Table S4) and summary likelihood ratio statistics in Table 3. Omnibus analyses revealed that the three-way interaction between participant group, priming and structure was marginally significant ($p = .0560$) for total time to begin writing but was not significant for either fine-grained measure. The two-way interaction between age group and structure was significant in total time to begin writing and trended toward significance in word access duration but was not significant in writing onset latency. The main effect of age group was highly significant for all measures with children responding much more slowly than adults. The main effect of structure was significant in total time to begin writing and word access duration, but not writing onset latency. No other main effects or interactions were significant (see Table 3). To gain further insight into the effects of structure, we explored the effects for adults and children separately.

Within the adult group (see Figure 2), the interactions between priming and structure were significant in both total time to begin writing (Panel A) and word access latency (Panel B), but not in writing onset latency (Panel C, see also Table 3). The main effect of priming was not significant in

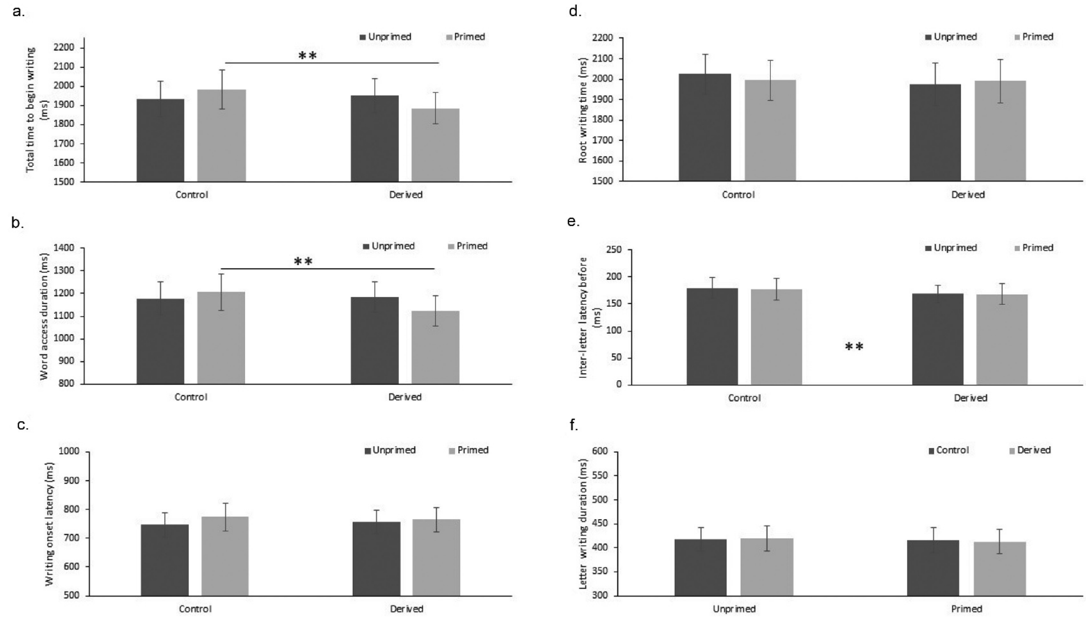

Figure 2. Adult mean latencies when spelling control and derived words in primed and unprimed conditions. *Note*. Error bars reflect standard errors. Significant differences indicated with asterisk (** $p < .001$, * $p < .05$). Panels A and B illustrate a significant main effect of structure (control, derived) in primed words. Panel E illustrates an overall main effect of structure.

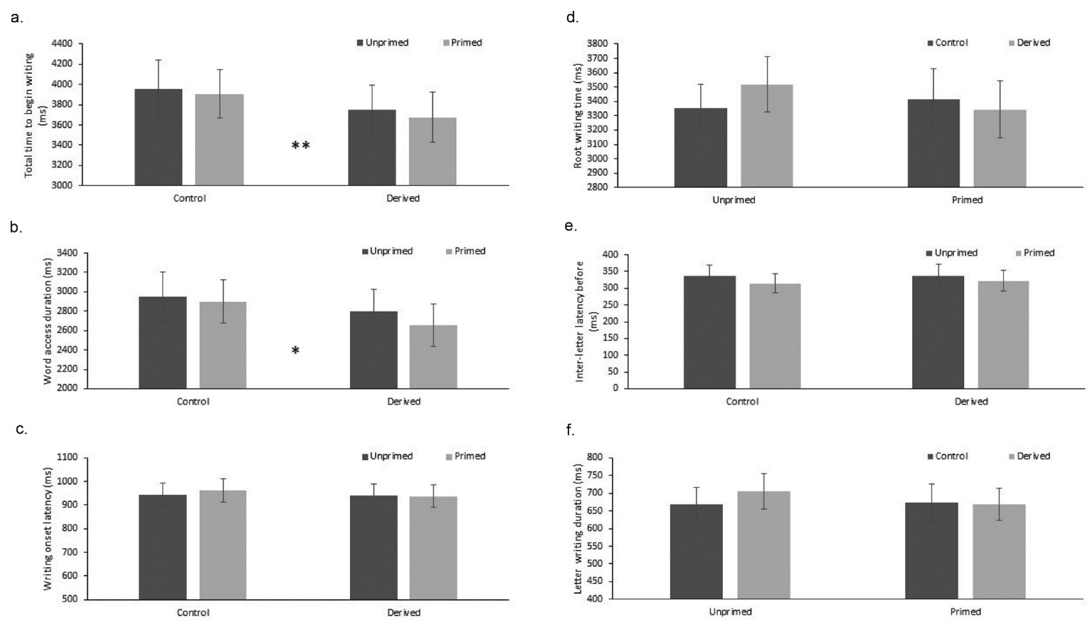

Figure 3. Child mean latencies when spelling control and derived words in primed and unprimed conditions. *Note*. Error bars reflect standard errors. Significant differences indicated with asterisk (** $p < .001$, * $p < .05$). Panels A and B illustrate significant main effects of structure (control, derived).

Table 3. Likelihood ratio tests of significance of interactions and main effects of age group (adults, children), priming (unprimed, primed) and structure (control, derived) in latencies before writing began in the spelling task.

		Total time to begin writing[b]	Word access duration[b]	Writing onset latency[b]
Omnibus	Age group*priming*structure	$\chi^2(1) = 0.33$, $p = 0560$	$\chi^2(1) = 0.01$, $p = .94$	$\chi^2(1) = 0.23$, $p = .63$
	Age group*priming	$\chi^2(1) = 0.10$, $p = .75$	$\chi^2(1) = 0.34$, $p = .56$	$\chi^2(1) = 0.39$, $p = .53$
	Age group*structure	$\chi^2(1) = 3.93$, $p = .0474$	$\chi^2(1) = 3.47$, $p = .06$	$\chi^2(1) = 0.26$, $p = .61$
	Priming*structure	$\chi^2(1) = 0.15$, $p = .70$	$\chi^2(1) = 0.66$, $p = .42$	$\chi^2(1) = 0.04$, $p = .85$
	Priming	$\chi^2(3) = 0.57$, $p = .90$	$\chi^2(3) = 2.48$, $p = .48$	$\chi^2(3) = 1.11$, $p = .77$
	Structure	$\chi^2(3) = 15.94$, $p = .0012$	$\chi^2(3) = 15.43$, $p = .0015$	$\chi^2(3) = 0.76$, $p = .86$
	Age group	$\chi^2(3) = 44.56$, $p < .0001$	$\chi^2(3) = 40.37$, $p < .0001$	$\chi^2(3) = 16.69$, $p = .0008$
Adults	Priming*structure	$\chi^2(1) = 5.84$, $p = .0157$	$\chi^2(1) = 5.53$, $p = .0187$	$\chi^2(1) = 0.67$, $p = .41$
	Priming	$\chi^2(1) = 0.11$, $p = .75$	$\chi^2(1) = 1.07$, $p = .30$	$\chi^2(1) = 2.91$, $p = .09$
	Structure	$\chi^2(1) = 3.71$, $p = .0542$	$\chi^2(1) = 4.49$, $p = .0340$	$\chi^2(1) = 0.01$, $p = .94$
Children	Age*Priming*Structure	$\chi^2(1) = 1.16$, $p = .28$	$\chi^2(1) = 1.25$, $p = .26$	$\chi^2(1) = 4.26$, $p = .0390$
	Priming*structure	$\chi^2(1) = 0.00$, $p = .99$	$\chi^2(1) = 0.26$, $p = .61$	$\chi^2(1) = 0.00$, $p = .95$
	Age*priming	$\chi^2(1) = 0.33$, $p = .57$	$\chi^2(1) = 2.11$, $p = .15$	$\chi^2(1) = 0.94$, $p = .33$
	Age*structure	$\chi^2(1) = 1.82$, $p = .18$	$\chi^2(1) = 0.27$, $p = .60$	$\chi^2(1) = 2.93$, $p = .09$
	Priming	$\chi^2(3) = 0.64$, $p = .89$	$\chi^2(4) = 3.97$, $p = .41$	$\chi^2(4) = 4.08$, $p = .39$
	Structure	$\chi^2(3) = 12.55$, $p = .0057$	$\chi^2(4) = 12.68$, $p = .0130$	$\chi^2(4) = 4.55$, $p = .34$
	Age	$\chi^2(3) = 2.72$, $p = .44$	$\chi^2(4) = 2.94$, $p = .57$	$\chi^2(4) = 5.02$, $p = .29$

Note: Random effects structure [a]+(1+Structure|Participant)+(1|RootWord), [b]+(1|Participant)+(1|RootWord), [c] +(1|Participant).

any measure. The main effect of structure was marginal in total time to begin writing and significant in word access latency. No other main effects or interactions were significant. Follow-up tests revealed that, for both total time to begin writing and word access duration, the observed interaction was the result of the main effect of structure, reaching significance for primed words $\chi^2(1) = 9.47$, $p = .0021$ and $\chi^2(1) = 10.17$, $p = .0014$, respectively, but not for unprimed words $\chi^2(1) = 0.13$, $p = .72$ and $\chi^2(1) = 0.08$, $p = .78$, respectively. In sum, total time to begin writing and word access duration indicated that adults were quicker to respond to derived words compared to controls, specifically in the primed condition.

Turning to the children (see Figure 3), we also explored whether there were any main effects or interactions with age as a continuous variable (in months). The three-way interaction between age, priming, and structure was significant in writing onset latency (see Table 3). The main effect of structure was significant both in total time to begin writing and word access duration (see Figure 3 Panels A and B). Children were faster to respond to derived words. This emerged in both the primed and unprimed conditions, as no other interactions were significant. There were no significant main effects. Follow-up tests exploring the three-way interaction in writing onset latency revealed that the interaction between age and priming was significant in control words $\chi^2(1) = 4.10$, $p = .0429$, but not for derived words ($p = .93$) and no other effects were significant ($p > .20$).

Findings from latencies before writing began are consistent with prior evidence – both adults and children respond more quickly to derived words than control words. Additionally, we found that this difference was significant only for adults for words that had been primed. Our novel analyses of both coarse- and fine-grained measures revealed that this effect is primarily caused by differences in word access duration not writing onset latency. Exploratory correlations between these measures (using item-level data from both adults and children) revealed significant relations in each case.[3] Total time to begin writing was highly correlated with word access duration $r(1549) = .98$, $p < .0001$ and less so with writing onset latency $r(1538) = .44$, $p < .0001$. The weakest relationship was between word access duration and writing onset latency $r(1533) = .29$, $p < .0001$. This weaker relationship between word access duration and writing onset latency is consistent with the idea that these measures tap into separate but related processes.

During spelling

First, we examined root writing time and then fine-grained measures during spelling – inter-letter latency between the last two letters of the root and letter writing duration for the last letter of the root. Panels D, E and F of Figures 2 and 3 illustrate overall means by participants. Model fit statistics are

Table 4. Likelihood ratio tests of significance of interactions and main effects of age group (adults, children), priming (unprimed, primed) and structure (control, derived) in latencies during writing in the spelling task.

		Root writing time [b]	Inter-letter latency between the last two letters of root[b]	Letter writing duration for last letter of root[b]
Omnibus	Age group*priming*structure	$\chi^2(1) = 0.43$, $p = .51$	$\chi^2(1) = 0.05$, $p = .82$	$\chi^2(1) = 0.22$, $p = .64$
	Age group*priming	$\chi^2(1) = 0.95$, $p = .33$	$\chi^2(1) = 1.11$, $p = .29$	$\chi^2(1) = 0.21$, $p = .65$
	Age group*structure	$\chi^2(1) = 0.59$, $p = .44$	$\chi^2(1) = 1.03$, $p = .31$	$\chi^2(1) = 0.89$, $p = .34$
	Priming*structure	$\chi^2(1) = 0.58$, $p = .45$	$\chi^2(1) = 0.08$, $p = .77$	$\chi^2(1) = 0.60$, $p = .44$
	Priming	$\chi^2(3) = 2.92$, $p = .40$	$\chi^2(3) = 3.18$, $p = .37$	$\chi^2(3) = 1.43$, $p = .70$
	Structure	$\chi^2(3) = 1.25$, $p = .74$	$\chi^2(3) = 1.16$, $p = .76$	$\chi^2(3) = 2.17$, $p = .54$
	Age group	$\chi^2(3) = 34.89$, $p < .0001$	$\chi^2(3) = 30.90$, $p < .0001$	$\chi^2(3) = 24.00$, $p < .0001$
Adults	Priming*structure	$\chi^2(1) = 0.11$, $p = .74$	$\chi^2(1) = 0.01$, $p = .91$	$\chi^2(1) = 0.23$, $p = .63$
	Priming	$\chi^2(1) = 0.00$, $p = .96$	$\chi^2(1) = 0.06$, $p = .81$	$\chi^2(1) = 0.08$, $p = .78$
	Structure	$\chi^2(1) = 1.68$, $p = .19$	$\chi^2(1) = 4.14$, $p = .0420$	$\chi^2(1) = 0.15$, $p = .70$
Children	Age*Priming*Structure	$\chi^2(1) = 4.79$, $p = .0286$	$\chi^2(1) = 0.00$, $p = .95$	$\chi^2(1) = 1.13$, $p = .29$
	Priming*structure	$\chi^2(1) = 0.65$, $p = .42$	$\chi^2(1) = 0.10$, $p = .75$	$\chi^2(1) = 0.6$, $p = .44$
	Age*structure	$\chi^2(1) = 0.10$, $p = .75$	$\chi^2(1) = 0.04$, $p = .85$	$\chi^2(1) = 0.75$, $p = .39$
	Age*priming	$\chi^2(1) = 0.09$, $p = .77$	$\chi^2(1) = 0.81$, $p = .37$	$\chi^2(1) = 2.66$, $p = .10$
	Priming	$\chi^2(4) = 2.22$, $p = .70$	$\chi^2(3) = 2.85$, $p = .42$	$\chi^2(4) = 4.44$, $p = .35$
	Structure	$\chi^2(4) = 1.19$, $p = .88$	$\chi^2(3) = 0.32$, $p = .96$	$\chi^2(4) = 4.91$, $p = .30$
	Age	$\chi^2(4) = 8.74$, $p = .08$	$\chi^2(3) = 1.04$, $p = .79$	$\chi^2(4) = 15.08$, $p = .0045$

Note: Random effects structure [a]+(1+Structure|Participant)+(1|RootWord), [b]+(1|Participant)+(1|RootWord), [c] +(1|Participant).

presented in supplementary materials (Table S5) and summary likelihood ratio statistics in Table 4. The omnibus analyses of latencies during spelling revealed that only the main effect of age group was significant, in all measures (*p*s < .0001). Planned comparisons were conducted within each group, which confirmed very few effects of word structure or priming during spelling.

For adults, there was a main effect of structure in the inter-letter latency between the last two letters of the root (see Table 4 and Figure 2 Panel E). Inter-letter latencies were shorter when these letters formed the end of the root morpheme in derived words than for the same letters in control words. No other effects or interactions were significant.

For children, the three-way interaction between age, priming, and structure was significant for root writing time but not in any fine-grained measures (see Table 4). The only fine-grained effect to reach significance was the main effect of age for letter writing duration for the last letter of the root (Figure 3 Panel F). Although the three-way interaction was significant in root writing time, follow-up tests confirmed that effects of structure and priming were not significant when explored separately. The main effect of age dominated latencies during spelling.

In summary, latency data revealed that both adults and children are influenced by morphological structure, responding more quickly to derived than control words. Effects of word structure are primarily observed before writing begins. In addition, we found that root priming increased the effect of word structure for adults (but not children). Our novel exploration of both coarse and fine-grained measures before and during spelling revealed that morphological structure also influenced inter-letter latencies, with adults demonstrating faster latencies between the last two letters of a root morpheme in derived than control words.

Discussion

This study delineates the multiple morphological processes theoretically identified to influence spelling (Levesque et al., 2021). A novel experimental approach disentangled effects of morphological processing during lexical access from those during spelling production. Adults and children (8–12;1 years) spelled two-morpheme derived (*art.ist*) and one-morpheme control words (*article*) shortly after completing an auditory lexical decision priming task. We examined accuracy, coarse-grained and fine-grained latencies before and during spelling to gauge underlying morphological processes. In adults, morphological processing was evident both during lexical access and during spelling production. In children, evidence of morphological processing was observed during lexical access but not during spelling production. The classic pattern of morphological facilitation in accuracy of spelling also emerged for children, supporting the validity of the paradigm. These findings extend limited prior research examining the time course of morphological processing in spelling and provide initial support for theoretical perspectives that suggest that spelling is affected not by one but by multiple morphological processes. These findings warrant a reexamination of theories of spelling, which traditionally focus on when in development changes occur, but need to also consider when the changes occur during the spelling process itself.

Morphological processing occurs during lexical access in spelling

Adults' spelling clearly reflected morphological processing during lexical access; indexed by the main effect of word structure in the latency data before spelling began and the morphological priming effect. Consistent with our hypotheses, coarse-grained latencies revealed effects of morphological processing before spelling began. This replicates Breadmore and Deacon's (2019) finding in spelling-to-dictation, using a different input modality. Here, adults' total time to begin spelling when stimuli were presented visually was faster for two-morpheme derived words than one-morpheme control words. Furthermore, adults demonstrated cross-modal morphological priming – the facilitatory effect of morphological structure was stronger when the root morpheme had been presented in the auditory lexical decision priming task. Fine-grained latencies also suggest that these effects of morphological processing occur during lexical access, since effects of morphological structure were significant in word access time but not in writing onset latency.

Like adults, children's latencies exposed the influence of morphological processing before spelling. Total time to begin writing was significantly faster for two-morpheme derived words (*art.ist*) than one-morpheme control words (*article*). Similar to the adult group, fine-grained analyses implicate morphological processing during word access (duration of the stimulus was presented on screen) but not in writing onset latency (duration between this and when writing began). These fine-grained analyses further support the view that these are effects of morphological processing during lexical access.

Additional evidence of morphological processing during lexical access comes from the priming effect, where developmental differences were observed. For adults, total time to begin writing was not only faster for derived words (*art.ist*) than control words (*article*), but morphological facilitation was stronger when the root morpheme (*art*) had been primed during the auditory lexical decision task. This cross-modal priming illustrates that morphological processing facilitated lexical access to a greater extent when the morphological properties of the target were pre-activated. These priming effects were observed in adults, but not children. This reinforces our view that morphological processing occurs during lexical access, and the impact on spelling develops with ability.

We used time before spelling commenced as a measure of lexical access. Our analyses suggest that word access duration and writing onset latency may tap into related but different processes (e.g., the small effect size of the correlation between these measures). Nonetheless, this is a preliminary investigation and further research should examine these processes more precisely. Spellers might already begin to prepare their response or spend more time inspecting stimuli when they know that they need to spell the word. This could be examined by testing whether writing onset times are similar to word reading times without spelling.

Morphological processing occurs during spelling production

We found subtle evidence of morphological processing during spelling production for adults but not children. This confirms that morphological processing has multiple influences on spelling. Analyses of fine-grained latencies identified effects of morphological processing obscured by coarse-grained analyses. Adults showed no significant effects of morphological priming or structure on root writing time but did show a significant effect of morphological structure on the inter-letter latency before the final letter of the root morpheme. This pause was significantly shorter for two-morpheme derived words than one-morpheme controls. This suggests a small but reliable facilitatory effect of morphological processing during spelling production, consistent with morphemes being used to hold the letters in memory. Children did not demonstrate any effects of morphological processing during spelling production.

Morphological processing changes over the course of development

Our findings add to limited previous research suggesting the nature of morphological processing and its impact on spelling changes over the course of development. Further research using longitudinal methods is needed to inform how and when morphological interventions might support spelling acquisition. Like us, Quémart and Lambert (2019) found developmental differences in the time course of morphological effects using a cross-sectional design, but our findings do not perfectly replicate theirs. They too found that adults showed effects of morphological processing before and during spelling, but effects during spelling were observed on the last letter of the first morpheme, whereas we observed differences on the inter-letter-latency between the last two letters of the first morpheme. Quémart and Lambert (2019) did not observe effects of morphological processing before spelling began in children (10- and 12-year olds), yet we observed this in children of the same age and younger (8- to 12-year olds). Quémart and Lambert (2019) observed morphological processing during spelling in letter writing durations for 12-year-old (but not 10-year-old) children. We did not observe effects during children's spelling. There are many methodological differences – the location of overlap between one-morpheme and two-morpheme words differed, the language differed, the age of participants differed. Further research can unpick these and other factors, such as morphological awareness and the role of instruction, to fully understand morphological processing in spelling.

The benefits and limitations of studying latencies in spelling

Latency data provide a means to study differences in performance after accuracy has been achieved. Analyses of correct spellings reveal continued development of underlying processes as spelling becomes more fluent and automatized. However, our findings also highlight a possible limitation of using handwriting latencies to explore the processes that underlie spelling production. The classic facilitative effects of morphological structure which have been documented elsewhere in spelling-to-dictation (Deacon et al., 2008 reviews) were observed here in children spelling a visually presented stimulus from memory – derived words were spelled more accurately than control words. However, children's handwriting latencies during spelling provided little evidence of morphological processing during spelling production. Perhaps, children do not use morphemes to hold the representation in working memory during spelling production. An alternative possibility though is that more random variance is introduced into children's latencies because their spelling and handwriting are slower and more disfluent or because of data loss due to behavioral factors. In which case, handwriting latencies might be less closely bound to underlying linguistic processes. From a theoretical perspective, this could be explained by variation in peripheral orthographic processes.

Despite careful familiarization with the procedure and reminders not to join letters, some children struggled to consistently follow this instruction. Inter-letter latencies and letter writing durations cannot be easily extracted for conjoined letters. Previous studies ensured that gaps were left between letters by asking participants to print in capital letters, but this introduces new issues (e.g., reducing ecological validity). Others have begun to explore changes in velocity of pen movements rather than latencies (e.g., Suárez-Coalla et al., 2020). This is an emerging area of research where more exploration of methods and measures is needed. Larger sample sizes and item pools would support generalization of findings and ensure that studies are not underpowered after data cleaning. Future research should also explore the impact of manipulating demands on peripheral orthographic processes (for example, printing in capital letters, typing, etc.).

Several aspects of the novel paradigm used here demand further reflection. We presented stimuli visually but then removed each stimulus before writing began. This ensured that participants had to hold the target in working memory while producing the spelling (which is facilitated by accessing the lexical entry for the word). In copying studies, visually presented stimuli remain available throughout the writing process (Kandel et al., 2008, 2012). Although we know that lexical access is achieved rapidly by skilled readers/writers (Lambert et al., 2011), under-developed cognitive skills make lexical access slower (McCutchen, 2000; Perfetti, 2007). Hence, when given the option to transcribe letter-by-letter rather than rely on their weaker lexicon, children may choose transcription if they do not benefit from accessing the lexicon. Hence, visual stimuli must be removed before spelling begins.

To measure word access duration, participants controlled the duration of exposure to stimuli. Consequentially, there was variation in exposure duration between participants and trials. As one would expect, children were clearly slower to access the target than adults (see word access durations illustrated in panel C in Figures 2 and 3). Moreover, one-morpheme control words were accessed more slowly than two-morpheme derivations. Future studies should examine the impact of controlling and manipulating exposure duration. Nonetheless, the present results are consistent with a previous study which used spelling-to-dictation (Breadmore & Deacon, 2019), supporting the validity of this method.

Finally, we applied cross-modal priming, a methodology commonly used to understand reading processes but rarely applied to spelling. Although the morphological priming effect was significant in adults' latencies, we found little evidence of morphological priming in children's spellings. This differs from another study which did demonstrate facilitatory effects in spelling (Rosa & Nunes, 2008). In that study, morphologically related primes and targets were presented and produced item-by-item (and within a sentence). Being temporally closer might have increased the priming effect, and the use of sentence completion might have influenced the nature of morphological processing (as morpho-syntactic processes are active). In our study, both prime and target were presented as isolated words and neither target nor prime was visible during spelling production. This may have increased difficulty and working memory load. Clearly, more can be learned from applying long lag and immediate priming to spelling. Further research should apply these techniques to other morphological structures (e.g., prefixes, inflections and compound words) and explore the mediating influence of other variables such as length, frequency, familiarity and semantic transparency.

Increasing evidence suggests that spelling is not a simple inversion of reading, and yet it has received very little attention. To further understand spelling processes, spelling paradigms need to be extended to resolve evidence gaps. Studies of the time course of morphological processing during spelling production are rare and tend to visually present stimuli and/or use typed responses. Yet, studies illustrating the positive impact of morphemes on children's spelling accuracy use spelling-to-dictation and handwritten responses (e.g., Deacon & Bryant, 2006a, 2006b). In real-world contexts, spellings are usually generated without the benefit of external stimuli (Turnbull et al., 2011). Variation in input may have important implications for lexical access and relative use of morphological decoding and/or analysis (see also Levesque et al., 2021). This needs empirical investigation by varying and contrasting task designs, not only to further theoretical understanding of spelling processes and development but also to make recommendations for education. The novel methods demonstrated here could, for example, be used to examine the impact of explicit instruction in morphological strategies on underlying cognitive processes.

Conclusions

The present study reveals evidence that the nature of morphological processing during spelling develops with age. Evidence from handwriting latencies and priming effects revealed that adults used morphological processing during lexical access as well as during spelling production. Children used morphological processing during lexical access but not during spelling production. Together, these findings highlight the multiple ways in which morphological processing influences spelling and how these change with the acquisition of spelling skill.

Notes

1. Derived and control words were well matched for number of letters $t(15) = -0.51$, $p = .62$; phonemes $t(15) = 0.68$, $p = .51$; syllables $t(15) = 0.37$, $p = .72$; neighbors $t(15) = -0.66$, $p = .52$; bigram type and token frequency $t(15) = 0.29$, $p = .77$ and $t(15) = -1.69$, $p = .11$; and the frequency of the bigram on the morpheme boundary between the root and the rest of the word $t(15) = -1.32$, $p = .21$.
2. Derived and control words were also matched for frequency on a range of measures; Zeno U $t(15) = -0.41$, $p = .69$; Grade 4 $t(15) = -1.37$, $p = .19$; Grade 5 $t(15) = -0.77$, $p = .45$; Grade 6 $t(15) = -0.70$, $p = .49$; Grade 7 $t(15) = -0.58$, $p = .57$; CELEX (overall) frequency $t(15) = -1.00$, $p = .33$; CELEX written frequency $t(15) = -0.08$, $p = .94$; log of CELEX written frequency $t(15) = -.16$, $p = .88$.
3. The effects were broadly similar when correlations were conducted on the adult and child data separately. Adults: Total time to begin writing was highly correlated with word access duration $r(609) = .88$, $p < .0001$ and less so with writing onset latency $r(611) = .60$, $p < .0001$. The weakest relationship was between word access duration and writing onset latency $r(609) = .16$, $p < .0001$. Children: Total time to begin writing was highly correlated with word access duration $r(938) = .97$, $p < .0001$ and less so with writing onset latency $r(938) = .29$, $p < .0001$. The weakest relationship was between word access duration and writing onset latency $r(922) = .15$, $p < .0001$.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Ethical review and approval was conducted by Dalhousie University Social Sciences and Humanities Research Ethics Board which followed the Government of Canada Tri-Council Policy Statement 2 (TCPS2, 2018), as well as Coventry University Ethics Committee. Written informed consent was obtained from parents and oral assent from children before inclusion in the study.

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ORCID

Helen L. Breadmore http://orcid.org/0000-0003-3050-8908
Emily Côté http://orcid.org/0000-0003-2948-4080
S. Hélène Deacon http://orcid.org/0000-0002-4792-5137

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