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Orthographic processing and children's word reading

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ABSTRACT
Theories of reading development generally agree that, in addition to phonological decoding, some kind of orthographic processing skill underlies the ability to learn to read words. However, there is a lack of clarity as to which aspect(s) of orthographic processing are key in reading development. We test here whether this is orthographic knowledge and/or orthographic learning. Whereas orthographic knowledge has been argued to reflect a child's existing *store* of orthographic representations, orthographic learning is concerned with the *ability to form* these representations. In a longitudinal study of second- and third-grade students, we evaluate the relations between these two aspects of orthographic processing and word-reading outcomes. The results of our analyses show that variance captured by orthographic knowledge overlaps with that of word reading, to the point that they form a single latent word-reading factor. In contrast, orthographic learning is distinctive from this factor. Further, structural equation modeling demonstrates that early orthographic learning was related to gains in word reading skills. We discuss the implications of these findings for theories of word-reading development.

Keywords: orthographic knowledge; orthographic learning; word reading

There is abundant evidence that children's ability to analyze the sound structure of words and to apply this to reading (i.e., phonological awareness and decoding) plays a strong, possibly causal role in reading acquisition (e.g., National Reading

Panel, 2000). Yet these skills do not account for all the variance in reading development (e.g., Juel, Griffith, & Gough, 1986; Tunmer & Nesdale, 1985). Dominant theories of reading development predict that *orthographic processing* is a key second force in reading acquisition, particularly in the transition to fluent word reading (e.g., Ehri, 1995; Share, 1995). Orthographic processing is commonly defined as the "ability to form, store, and access orthographic representations" (Stanovich & West, 1989, p. 404). In other view this broad definition captures within it potentially separable aspects of orthographic processing. In particular, a distinction can be made between orthographic knowledge, which is the child's crystallised *store* of orthographic representations, and orthographic learning, which is the child's dynamic *ability to form* these representations. A key theoretical question lies in which of these aspects of orthographic processing plays a role in the acquisition of skilled reading. For instance, is there a distinct, and measurable, orthographic learning ability that promotes word-reading development? To answer this question, we explore the relations between orthographic knowledge, orthographic learning, and children's word-reading development.

Standard measures of orthographic knowledge index a child's existing level of knowledge, rather than their dynamic learning capacity, at both lexical and sublexical levels. At the lexical, or whole-word, level, orthographic choice tasks require the child to select the correctly spelled word from a pseudohomophonic foil (e.g., *rane – rain*; Olson, Forsberg, Wise, & Rack, 1994). At the sublexical, or letter–pattern, level, the tasks may involve selecting which of two options is most likely to be a word when one violates orthographic regularities (e.g., *baff – bbaf*; Cassar & Treiman, 1997; see also Treiman, 2017). It is possible that existing orthographic knowledge measured at the lexical and sublexical levels might be key in predicting subsequent gains in reading acquisition. From a purely methodological perspective, this crystalized knowledge, as measured by lexical and sublexical choice tasks, may index the child's prior learning success, with prior learning known to be a good predictor of future learning (see, e.g., Wang, Nickels, Nation, & Castles, 2013). From a theoretical perspective, the quality and extent of a child's existing orthographic knowledge might directly support his or her subsequent reading acquisition by providing a rich, efficient, and structured network within which new information can be readily incorporated. For example, in both the Lexical Quality Hypothesis (Perfetti & Hart, 2002) and the recent Lexical Legacy Hypothesis (Nation, 2017), individual differences in the quality of orthographic representations result in differences in online lexical processing, which in turn affect the child's capacity to acquire further reading experience and skills.

In contrast, according to the Self-Teaching Hypothesis, the key aspect of orthographic processing that drives reading development is a distinct, measurable skill representing the child's dynamic orthographic learning ability, rather than his or her preexisting knowledge (Share, 1995). For example, Share (2011, p. 53) articulates that "over and above the ability to decode unfamiliar words, there exist individual differences in the speed and accuracy with which word-specific (and general) orthographic knowledge is assimilated. Thus, visual/orthographic ability is seen not merely as a secondary source of variance, but as a secondary source of individual differences in printed word learning" (although see Burt, 2006, for a contrary view). Share's ideas build on pioneering work on the concept of orthographic mapping by Ehri (e.g., Ehri & Roberts, 1979). The self-teaching idea takes this one step further; according to the Self-Teaching Hypothesis, the key orthographic learning capacity reflects children's skill in acquiring new orthographic representations through independent reading of naturalistic texts. If orthographic learning is a "secondary source of individual differences in reading acquisition" (Share, 1999, p. 98), then a dynamic measure of children's ability to acquire new orthographic representations through their reading of naturalistic texts should be related to word-reading development.

Most available data evaluating these theoretical predictions emerge from correlational studies at a single point in time. Multiple studies have reported correlations between orthographic knowledge (measured with lexical and/or sublexical tasks) and word-reading outcomes. These relations have been demonstrated with word-reading accuracy and efficiency (e.g., Barker, Torgesen, & Wagner, 1992; Conners, Loveall, Moore, Hume, & Maddox, 2011; Conrad, Harris, & Williams, 2013; Cunningham, 2006; Katzir et al., 2006). These relations remain after controlling for potential confounds, such as phonological awareness (e.g., Conners et al., 2011; Conrad et al., 2013). The majority of these studies have been conducted with 7- to 9-year-old children. Several of these studies have shown independent contributions of both lexical and sublexical orthographic knowledge to word reading (e.g., Conners et al., 2011; Conrad et al., 2013). A much smaller body of work shows that children's orthographic learning is correlated with word reading (Bowey & Miller, 2007; Ricketts, Bishop, Pimperton, & Nation, 2011). In these studies, children were asked to read a series of texts, each of which includes a novel word (e.g., *feap*). Children were then assessed for their ability to recognize and/or spell the new word correctly. Ricketts et al. (2011) found a trend toward relations between 7- and 8-year-old children's word-reading efficiency and accuracy and their performance on two measures of orthographic learning (i.e., spelling and orthographic choice), after controlling for nonverbal reasoning and target word decoding (see Bowey & Miller, 2007; Mimeau, Ricketts, & Deacon, 2018). Together, these studies point to associations between both children's existing orthographic knowledge and their dynamic orthographic learning with their word reading.

Evidence of correlations between children's orthographic knowledge and their word reading at a single point in time have often been interpreted as suggesting that orthographic knowledge drives growth in word reading (e.g., Olson et al., 1994; for reviews, see Burt, 2006; Castles & Nation, 2006). Similar speculations have been made about such associations with orthographic learning (e.g., Bowey & Miller, 2007). Yet evidence of correlation, even when it remains beyond multiple control variables, does not establish that orthographic knowledge is responsible for the acquisition of word-reading skills. Nor do correlations between orthographic learning and word reading (as in Cunningham, 2006) provide convincing evidence that orthographic learning is key in word-reading acquisition (as in Share, 2011). The studies to date do not provide the critical developmental test of these theories: evaluating whether either orthographic knowledge or orthographic learning, or both, determine gains in word-reading outcomes.

One way to assess these predictions lies in the use of autoregressor analyses of a longitudinal study (Kenny, 1975). One can assess, for example, whether early orthographic knowledge or learning predicts gains in word reading. Controlling for the autoregressor, or the prior level of the outcome variable, permits the conclusion that the early orthographic skill of interest is associated with *change* in, and not merely later levels of, word reading. That said, these analyses rely on adequate variability in children's gains in reading skills; this can be a challenge given the fact that individual differences in children's reading development are incredibly stable (e.g., Hulslander, Olson, Willcutt, & Wadsworth, 2010). Further, controlling for the autoregressor effectively controls for any preexisting effects that the variable of interest has already had in determining word-reading skills to that point (e.g., Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). As such, these are considered highly conservative analyses.

In terms of orthographic knowledge, there is conflicting evidence to date as to the temporal order of its relations with word reading. Two early studies found that orthographic knowledge predicted gains in word-reading accuracy, one from Grade 1 to 2 (Wagner & Barker, 1994) and the other from Grade 2 to 3 (Cunningham, Perry, & Stanovich, 2001). In Wagner and Barker's (1994) study, the orthographic knowledge composite included lexical orthographic knowledge, concepts of print, and letter knowledge. In Cunningham et al.'s (2001) study, orthographic knowledge was measured with three tasks: lexical and sublexical orthographic knowledge and word spelling. Three more recent studies focused on more targeted measures of orthographic knowledge, each detecting no significant relations between early orthographic knowledge and word-reading acquisition. In a longitudinal study of Grade 1 and 2 children, Georgiou, Parrila, and Papadopoulos (2008) found no significant contribution of lexical orthographic knowledge to gains in word-reading efficiency or text-reading fluency. In their longitudinal study of children in Grades 1 to 3, Deacon, Benere, and Castles (2012; see also Conrad & Deacon, 2016) found no significant contribution of either lexical or sublexical orthographic knowledge to gains in word-reading accuracy. Instead, children's early word-reading accuracy contributed to gains in lexical and sublexical orthographic knowledge, as predicted by Ehri (2005). These latter studies have not detected a significant contribution of early orthographic knowledge to gains in word-reading skills. That said, given the variation in findings across studies, this conclusion would benefit from further empirical confirmation with more sophisticated statistical analyses, including evaluating whether orthographic knowledge is distinctive from word reading.

None of these studies evaluates the possibility that orthographic learning capacity might be independently associated with gains in word reading. This is one interpretation of the findings to date showing correlations (e.g., Ricketts et al., 2011), but it needs to be tested empirically. In doing so, one needs to remain wary that relations could work in both directions, as pointed out by several research groups (Deacon et al., 2012; Wolter, Self, & Apel, 2011).

Children's initial orthographic learning skill could enable their acquisition of word reading, and their word-reading ability could also support their orthographic learning (see also Wang et al., 2013).

THE PRESENT STUDY

In the study that we report on here, we sought to contribute to theories specifying the role of orthographic processing in word-reading development by evaluating the relations between each of orthographic knowledge and orthographic learning with children's word-reading development.

We conducted a longitudinal study for which we recruited children in two different grades at the beginning of the study: Grades 2 and 3. We build on our prior work with this sample in which we focused on orthographic knowledge at the lexical level (Conrad & Deacon, 2016). Here, we report on data primarily from two time points of the study: at the ends of Grades 2 and 3 and 12 months later at the ends of Grades 3 and 4. This is the period in which theories of word reading predict that children will use letter patterns in their reading (e.g., consolidated alphabetic phase; Ehri, 1995). At each time point, children completed measures of orthographic knowledge and learning and three different measures of word reading.

Our measures of orthographic knowledge and learning build on and extend widely used measures from prior studies. We assessed orthographic knowledge with the two most common measures: lexical (e.g., *rain* – *rane*; Olson et al., 1994) and sublexical (e.g., *waught* – *waut*; Conrad et al., 2013). For orthographic learning, we drew on the one available measure of orthographic learning designed to evaluate individual differences in learning of lexical-level representations (Byrne et al., 2008). Most prior studies included only a small set of items (typically 6 or 8; e.g., Ricketts et al., 2011) restricting assessment of individual differences. Byrne et al. (2008) designed a task with 15 items, specifically to evaluate genetic influences on individual differences in orthographic learning. This task is well suited to address our questions of the relations between individual differences in orthographic learning and progress in acquiring word reading. In our orthographic learning task, children read independently short stories containing novel words. As in Byrne et al. (2008), we provided the child with the correct pronunciation if the child was not able to read the target word during the orthographic learning task. Following on Byrne et al., we did so to reduce the influence of decoding on orthographic learning. Doing so focused more specifically on Share's (2011) prediction that individual differences in orthographic learning capacity, over and above those in phonological decoding, determine word-reading acquisition. We measured immediate orthographic learning by asking children to complete both an orthographic choice and a spelling measure immediately following the learning task (see, e.g., Ouellette & Fraser, 2009; Ricketts et al., 2011; Share 2007; Wang et al., 2013). We also measured the long-term retention of this orthographic learning in a delayed orthographic choice task two days later (e.g., Ouellette & Fraser, 2009; Share, 2007).

In terms of word reading, we included multiple measures to capture several aspects of this complex skill. The end goal of models of word-reading acquisition is efficient word-reading skills. This is characterised by accurate, but also rapid and automatic recognition of individual words (e.g., Ehri, 2005; Perfetti, 2007). As such, we included measures of word-reading accuracy and efficiency. In terms of word-reading accuracy, it is also important to measure reading of irregular words that do not strictly follow letter–sound correspondences, such as *yacht*. Orthographic learning factors have been argued to predict gains in reading irregular words, as phonological decoding alone is not effective for access to their meaning and pronunciation (e.g., Ricketts et al., 2011; Wang, Castles, Nickels, & Nation, 2011). We included measures of word-reading accuracy and efficiency across a wide range of measures and a task specifically targeting irregular word reading.

We first evaluated empirically the separability of the aspects of orthographic processing from word reading itself (Burt, 2006; Castles & Nation, 2006). Prior evidence of separable contributions of lexical and sublexical orthographic knowledge to word reading (e.g., Conrad et al., 2013) point to this possibility, but do not test it directly. The need to do so is supported by prior factor analyses. These have shown that performance on orthographic knowledge tasks load on a single factor; although this factor is separable from phonological dimensions, it is also clearly correlated with word reading (e.g., Cunningham et al., 2001; Hagiliassis, Pratt, & Johnston, 2006). To the best of our knowledge, these are the first factor analyses of performance on orthographic learning tasks as they relate to word reading.

We also modeled the relations between orthographic processing and word reading. Based on the Self-Teaching Hypothesis, we predicted that children's learning capacity, rather than their acquired repository of knowledge, should determine word-reading development in this age range. In the other direction, we suspected that word-reading skills would predict development in both orthographic knowledge and orthographic learning. This is in keeping with prior speculations that children's skills in word reading might enable gains in their orthographic learning (e.g., Wang et al., 2013) and prior evidence that children's word reading enables improvement in orthographic knowledge (e.g., Deacon et al., 2012). In assessing these relations, we controlled for phonological awareness (e.g., Ouellette & Fraser, 2009) and nonverbal reasoning (e.g., Ricketts et al., 2011) given widespread evidence of their relationship to word reading (Ehri et al., 2001).

METHOD

Participants

A total of 125 children from four different schools in Eastern Canada were initially recruited into a longitudinal study. Children were recruited in Grades 2 and 3, and we conducted testing over two academic years (into their Grades 3 and 4, respectively). We excluded participants who did not meet our inclusion criteria (developmental disorders, $n = 5$, English not first language, $n = 3$), or who had incomplete demographic data ($n = 5$).

Thus, our final sample included in analyses consisted of 112 participants, 56 starting in Grade 2 (22 male, 34 female) and 56 in Grade 3 (29 male, 27 female). We report here on data collected primarily from two time points in a longitudinal study. In this manuscript we refer to Time 1 as the spring of Grades 2 and 3 and we refer to Time 2 as the spring of Grades 3 and 4. The children in Grades 2 and 3 were 7.91 ($SD = 0.29$) years and 9.03 years ($SD = 0.35$), respectively, at Time 1 and they were 8.90 years ($SD = 0.28$) and 10.01 years ($SD = 0.35$) at Time 2, respectively.

Procedure and measures

We report here on data collected primarily from two time points in a longitudinal study. Time 1 testing occurred near the end of either Grade 2 or Grade 3, and Time 2 testing occurred approximately 12 months after Time 1, near the end of Grades 3 and 4. There were two testing sessions in each of Time 1 and 2, each separated by 2 or 3 days. In Session 1 of Time 1, we assessed lexical and sublexical orthographic knowledge, word-reading efficiency, word-reading accuracy, and irregular word reading. In this session, we also conducted the orthographic learning task, along with both immediate outcome measures (spelling and orthographic choice). In Session 2 of Time 1, children completed the delayed orthographic choice task following orthographic learning. The tasks in Sessions 1 and 2 of Time 2 were the same as in Sessions 1 and 2 of Time 1, with the addition of the nonverbal reasoning measure as the final task in the battery in Session 2. Data for phonological awareness came from a testing point in the longitudinal study that was 6 months prior to Time 1 that we report on here. All testing took place one-on-one with a researcher in a quiet room.

Reliabilities for each measure are reported in Table 1. All standardised measures (i.e., phonological awareness, word-reading accuracy, word-reading efficiency, and nonverbal reasoning) were administered according to manual instructions. For tasks administered at two time points, we used different forms at each time point for measures for which parallel forms were available (i.e., for standardized measures of word identification and Test of Word Reading Efficiency) and in cases where we could have reasonable confidence in our ability to create parallel forms (i.e., orthographic learning).

Word-reading accuracy. The word identification subtest from the Woodcock Reading Mastery Test—Revised (Woodcock, 1998) was used to measure word-reading accuracy. In this task, children are asked to read aloud words that get progressively more difficult. At Times 1 and 2, we used alternate forms.

Word-reading efficiency. The word-reading efficiency subtest the Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999) was administered as a measure of word-reading efficiency. This is a timed word-reading task in which participants have 45 s to read a list of words. Scores are based on how many words the participant can correctly read in this time. We used alternate forms at Times 1 and 2.

Table 1. *Means, standard deviations, skewness, and reliabilities for the experimental and standardized tests; reliability for the experimental tests was calculated across participants reported on here, and reliability for the standardized tests was taken from the manuals of the tests*

	Time 1				Time 2			
Measure	*Mean/Max.*	*SD*	Skewness	Reliability	*Mean/Max.*	*SD*	Skewness	Reliability
Orthographic learning								
Orthographic choice immediate								
Raw score	9.00/15	3.13	–0.14	.72	10.27/15	2.88	–0.51	.63
Orthographic choice delayed								
Raw score	8.53/15	3.16	–0.01	.71	9.81/15	2.77	–0.28	.64
Spelling								
Raw score	7.65/15	3.84	0.03	.82	9.31/15	3.68	–0.37	.82
Decoding accuracy								
Raw score	49.26/60	8.84	–1.37	.87	51.66/60	7.65	–1.57	.91
Orthographic knowledge								
Orthographic choice								
Raw score	31.09/36	4.82	–1.09	.87	48.85/61	6.37	–0.76	.82
Word-likeness								
Raw score	30.59/42	4.98	–0.59	.73	43.53/60	5.98	–0.77	.70
Word reading								
Irregular word reading								
Raw score	17.85/40	5.86	–0.78	.92	21.32/40	5.32	–0.97	.92
Standard score	0.03	0.98	–0.40		0.02	0.96	–0.29	
Word identification								
Raw score	55.93/106	12.51	–1.00	.91–.98	63.23/106	12.00	–0.46	.91–.98
Grade-based standard score	99.08	11.51	0.44		99.03	11.20	0.26	

TOWRE: Sight word subtest								
Raw score	57.79/104	14.30	–1.12	.90–.97	62.32/104	11.98	–1.32	.90–.97
Standard score	107.29	13.05	–0.78		103.90	12.48	–0.53	
Nonverbal reasoning								
Raw score	13.86/32	6.76	0.10	.93–.94	—	—	—	—
Standard score	46.34	10.80	–0.01					
Phonological awareness								
Raw score	9.72/20	4.16	0.93	.89–.91				
Standard score	9.28	2.47	0.94		—	—	—	—
Age (months)	101.56	7.74	0.15	—	113.33	7.73	0.18	

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Irregular word reading. A subset of items from the Castles and Coltheart Test 2 (Castles et al., 2009) was used to measure irregular word-reading ability. Children are asked to read a set of 40 irregular words, which are presented individually on cue cards, and continue until 5 consecutive words are read incorrectly. We used the same list of words at each testing point, as there is no available alternate form and there is evidence that there are unlikely to be test–retest effects (McArthur, Ellis, Atkinson, & Coltheart, 2008).

Lexical orthographic knowledge. Children are provided with a sheet containing homophonic spellings, one of which is a real word (e.g., *explain* – *explane*). Children are asked to choose the correct spelling for the word; they were not provided with the pronunciations. There were 36 items at Time 1 (from Olson et al., 1994), and an additional 25 items (from both Olson et al., 1994, and Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009) were added at Time 2 to a total of 61. Additional items were added to reduce the possibility of ceiling effects at Time 2. We did not use alternate forms at the two time points (see Deacon et al., 2012), given the lack of available parallel form and a lack of ability to ensure comparability difficulty in a second set of items.

Sublexical orthographic knowledge. Children were presented with homophonic nonword pairs or triplet sets. Some of the sets contrasted legal versus illegal spellings (e.g., *screigh* – *scraie*) and others contrasted more or less frequent spellings (e.g., *waught* vs. *waut*; based on the MRC Psycholinguistic Database; Ziegler et al., 1997). The latter set were included to increase task difficulty. Regardless of the item type, there was one correct response (based on legality or frequency) and one or two distractors that were homophonic with the correct response. Children were asked to circle the nonword that looked most like a real word. They were not provided with the pronunciations. There were 42 items at Time 1 (based on Conrad et al., 2013). To ensure that children did not hit ceiling, an additional 18 items were added at Time 2, for a total of 60 items. At Time 3, 12 of the additional items were triplet sets. We did not use a new version at the second time point, given the lack of available parallel form and the limited number of orthographic patterns that can be included in such a task.

Orthographic learning. Based on Byrne et al. (2008), children were asked to read 15 stories out loud; each of these stories included four repetitions of a nonword. For example, "The new word is Laif. The coldest town in the world is Laif. Laif is in Greenland. The people who live in Laif need very hot houses." We used the stories and nonwords from Byrne et al. (2008) at Time 1 testing. There was a homophone pair for each story (e.g., *laif* – *lafe*); one half of the children saw one of the nonwords and the other half saw the other nonword (e.g., *laif* and *lafe*, respectively). At Time 2, we created parallel nonwords and stories. For the nonwords, we changed one or two consonants from the items at Time 1, retaining the target spellings (e.g., *laif* – *lafe* was changed to *laip* – *lape*). We applied the same approach to altering the distractors for the orthographic choice task. The stories were revised by changing the semantic content, but maintaining the sentence structure, overall word frequency ($p = .69$), and number of words. As an example, the sentence “The coldest town in the world is Laif” became “The fastest car in the world is a Fafe.”

Orthographic learning was measured with both spelling and orthographic choice tasks. Based on Byrne et al., children read the stories in blocks of three and children’s spelling of the novel words was assessed after each block. Spelling was assessed in a dictation format, with the nonword provided orally to the child. Following their reading of all of the stories, the children completed an orthographic learning choice task in which they were asked to choose the spelling for the nonword that they read in the stories from a set of four nonwords. The children were not provided with any pronunciations. These four nonwords were the two homophones of the nonwords that they read (e.g., *laif* and *lafe*) and two visual distractors (e.g., *laip* and *lape*). Distractors for both Time 1 and Time 2 were created by altering a consonant in the target nonwords. For both target nonwords and distractors, we ensured that these were not obscure real words (by consulting *Merriam-Webster’s Collegiate Dictionary*, 2005) and we ensured that they did not contain smaller words that were longer than four letters. Children completed the orthographic choice task again 2 days later.

Based on Byrne et al. (2008), we supplied the correct pronunciation in cases in which the child erred or was not able to read the target word. We tracked children’s accuracy in pronouncing the nonwords; this was the orthographic learning decoding score (see, e.g., Nation, Angells, & Castles, 2007). This score was out of a maximum of 60, as children had four opportunities to decode each of the 15 target words.

Phonological awareness. We administered the elision subtest of the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999). In this task, children hear a word and are asked to say what is left once part of that word is eliminated (e.g., “Say *tiger* without saying /g/”).

Nonverbal reasoning. Nonverbal reasoning was measured using the matrix subtest of the Weschler Abbreviated Scale of Intelligence (Weschler, 1999). In this task, participants are presented with a matrix from which a section is missing; participants must choose the image that completes the matrix from a set of five choices.

RESULTS

Descriptives (raw scores) and reliabilities for each task can be found in Table 1. We also report norm scores for standardized assessments. Reliabilities are all at or above .6, the minimum acceptable for experimental measures.

All variables were examined for missing values, floor and ceiling effects, univariate and multivariate outliers, and normality. There were no floor or ceiling effects, and the data were complete for all tasks except for the delayed orthographic learning measure at Time 1. Table 2 displays Pearson correlations between all variables and composites with data combined across the entire

Table 2. *Correlation matrix*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. T1 OL decoding acc.																				
2. T2 OL decoding acc.	.82																			
3. T1 OL immediate	.47	.43																		
4. T2 OL immediate	.39	.25	.59																	
5. T1 OL spelling	.63	.56	.64	.48																
6. T2 OL spelling	.57	.56	.55	.72	.67															
7. T1 OL delayed	.44	.34	.72	.52	.54	.56														
8. T2 OL delayed	.32	.35	.52	.80	.43	.67	.44													
9. T1 OK lexical	.56	.45	.43	.46	.45	.49	.43	.49												
10. T2 OK lexical	.55	.55	.51	.48	.51	.44	.40	.46	.75											
11. T1 OK sublexical	.55	.47	.52	.43	.51	.47	.51	.41	.73	.75										
12. T2 OK sublexical	.54	.53	.32	.29	.44	.43	.34	.34	.61	.64	.63									
13. T1 Word identification	.81	.77	.54	.49	.61	.58	.50	.49	.71	.74	.71	.63								
14. T2 Word identification	.75	.74	.50	.54	.60	.60	.44	.52	.61	.68	.58	.53	.84							
15. T1 TOWRE	.81	.72	.54	.46	.56	.52	.48	.40	.71	.75	.70	.59	.87	.77						
16. T2 TOWRE	.77	.76	.49	.36	.52	.46	.41	.34	.61	.69	.61	.53	.84	.79	.87					
17. T1 Irreg. word reading	.78	.73	.58	.49	.63	.63	.55	.47	.75	.74	.76	.67	.92	.82	.85	.80				
18. T2 Irreg. word reading	.74	.76	.57	.47	.62	.59	.49	.53	.70	.73	.67	.56	.89	.80	.83	.81	.88			
19. T1 Phon. awareness	.54	.46	.26	.24	.53	.42	.26	.25	.33	.43	.34	.37	.53	.58	.47	.42	.53	.48		
20. T1 Nonverbal reasoning	.27	.17	.10	.06	.08	.15	.17	.06	.17	.16	.18	.19	.23	.26	.24	.21	.26	.25	.08	
21. T1 Age	.26	.19	.26	.09	.29	.18	.26	.10	.36	.29	.39	.26	.37	.24	.35	.23	.40	.31	.19	.24

Note: OL, orthographic learning. Acc., accuracy. OK, orthographic knowledge. TOWRE, Test of Word Reading Efficiency. Irreg., irregular. Phon., phonemic. *r*s > .21 are significant at $p < .05$.

sample. Except for nonverbal reasoning, all predictor variables (phonological awareness, orthographic knowledge, and orthographic learning skills) were significantly positively correlated with the three word-reading measures.

Below we will first present the outcomes of the confirmatory factor analyses (CFA). The goal of these analyses was to evaluate the separability of the orthographic knowledge, orthographic learning, and word-reading constructs. Next we will proceed with the results of the path analyses to examine the longitudinal relations between word reading and orthographic processing.

CFA

Structural equation modeling was used to construct and compare multiple latent variables with CFA. To do so, we constructed and compared three models. Figure 1 displays the theoretical factor models that were tested, separately at Times 1 and 2. Model 1 tests a one-factor solution, with all measures of word reading and orthographic processing (both orthographic knowledge and orthographic learning) loaded onto a single factor. Model 2 tests a two-factor model, where one latent factor consists of the word-reading and orthographic knowledge measures, and the other factor consists of the orthographic learning measures. Model 3 tests a three-factor model, where the latent factors consist of the (a) word-reading, (b) orthographic knowledge, and (c) orthographic learning

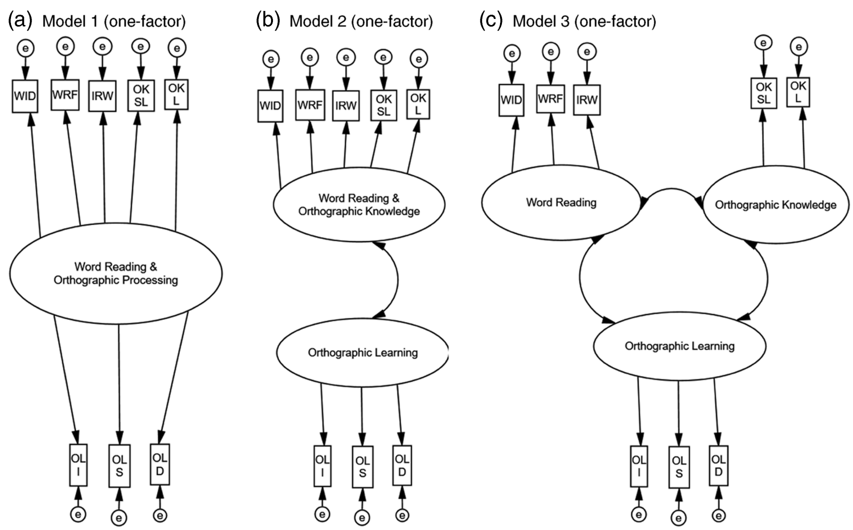

Figure 1. Theoretical models for (a) one-, (b) two-, and (c) three-factor solutions tested at Time 1 and Time 2, separately.
WID, word identification. WRF, word-reading fluency. IWR, irregular word reading. OK L, orthographic knowledge lexical. OK SL, orthographic knowledge sublexical. OL, orthographic learning. I, initial. S, spelling. D, delayed.

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measures. Latent factors in Models 2 and 3 were allowed to correlate. Comparisons between models test whether the measures of orthographic processing (both knowledge and learning) tap the same construct as the word-reading measures or are unique factors.

Multiple fit indices were used to compare factor models, including the chi-square test, root mean square error of approximation (RMSEA), comparative fit index (CFI), and Akaike information criterion (AIC). A χ^2 to *df* ratio of <3 suggested a good fit (Kline, 1998). CFI values can range from 0 to 1, with larger numbers indicating better model fits. An acceptable model fit is indicated by a CFI value of .90 or larger. RMSEA values can range from 0 to 1, with smaller numbers indicating better model fit. An acceptable model fit is indicated by a RMSEA value of <.10 (Marsh, Hau, & Grayson, 2005; Marsh, Hau, & Wen, 2004). Smaller numbers for the AIC indicate better model fit. Deviance statistics were calculated by taking the difference of the AIC and *df* between Models 1 and 2, and 1 and 3. If the deviance statistic is significant, the model with the lower values fits significantly better and is the preferred model (Browne & Cudeck, 1993; Kenny, Kashy, & Cook, 2006). However, statisticians caution against strict reliance on using cutoff scores to determine if a model should be accepted or rejected (Chen, Curran, Bollen, Kirby, & Paxton, 2008; Fan & Sivo, 2005; Kenny, Kaniskan, & McCoach, 2011; Marsh et al., 2004), suggesting that models that do not satisfy all fit statistics can still be informative regarding predictive relationships (Barrett, 2007).

Table 3 presents fit indices for the factor models that were compared. We first review the models at Time 1. Model 1 at Time 1 displayed acceptable fit for CFI, and a poor fit statistic for RMSEA. Fit statistics for Model 2 at Time 1 fell into the acceptable range. The correlation between the latent factor of word reading/orthographic knowledge and orthographic learning was .72, $p<.001$. The deviance statistic between Models 1 and 2 at Time 1 was significant, and the lower AIC suggests that Model 2 fits significantly better than Model 1. Model 3 at Time 1 also had fit statistics in the acceptable range. However, Model 3 did not fit significantly better than Model 2, suggesting that, in this sample, the measures of orthographic knowledge are highly aligned with the word-reading measures. The two-factor model was the most parsimonious solution that represented the data better than the one-factor model solution. The results strongly suggest that the measures of orthographic learning should be separated as a unique factor from word reading at Time 1 and that word reading should be considered together with orthographic knowledge.

For factor models at Time 2, Model 1 displayed poor fit statistics for the CFI and RMSEA values. Fit statistics for Model 2 at Time 2 was acceptable for CFI, but not for RMSEA. The correlation between the latent factor combining word reading and orthographic knowledge with orthographic learning was .63, $p<.001$. The deviance statistic between Models 1 and 2 at Time 2 was significant, and the lower AIC suggests that Model 2 fits significantly better than Model 1. Model 3 also had fit statistics in the acceptable range for CFI but not for RMSEA. However, Model 3 did not fit significantly better than Model 2. Similar to the Time 1 results, at Time 2 the two-factor model was the most parsimonious

Table 3. *Fit statistics for CFA and path models*

	χ^2	*df*	χ^2/df	*p*	CFI	RMSEA	AIC	ΔAIC	Δ*df*	*p*
Factor models at Time 1										
1-factor model	79.00	20	3.95	<.001	0.94	.16	75.41			
2-factor model	30.81	19	1.62	.042	0.98	.08	64.81	10.6	1	.001
3-factor model	21.67	17	1.28	.198	0.99	.05	59.67	5.14	2	.077
Factor models at Time 2										
1-factor model	144.53	20	7.23	<.001	0.78	.26	176.53			
2-factor model	48.47	19	2.55	<.001	0.95	.13	82.47	94.06	1	<.001
3-factor model	39.13	17	2.30	.002	0.96	.12	77.13	5.34	2	.069
Longitudinal path models										
4-factor baseline	281.39	141	2.00	<.001	0.91	.10	417.39			
4-factor with WR to OL	278.66	140	1.99	<.001	0.91	.10	416.65	0.74	1	.55
4-factor with OL to WR	221.81	140	1.58	<.001	0.95	.08	359.81	57.58	1	<.001
4-factor with both	219.07	139	1.58	<.001	0.95	.08	359.97	57.42	2	<.001

Note: CFI, comparative fit index. RMSEA, root mean square error of approximation. AIC, Akaike information criterion. OL, orthographic learning. WR, word reading. Delta (Δ) statistics for the factor models compare the model immediately above it. Comparisons for the path models are between the baseline and the orthographic learning models.

solution that represented the data better than the one-factor model solution. Again, the results suggest that the measures of orthographic learning should be separated as a unique factor from word reading, but that measures of orthographic knowledge fit best within a latent factor of word reading. Correlations within three factor models further support this interpretation; in these models, the correlation between latent constructs of orthographic knowledge and word reading are .91 and .86 at Times 1 and 2, respectively (all *ps* <.001); this is in sharp contrast to the correlations between the latent constructs of orthographic learning and orthographic knowledge which are .68 and .58 at Times 1 and 2, respectively.

Figure 2 presents the preferred two-factor models for Times 1 and 2. The percentage of variance explained (R^2) by the latent factors is shown in *italics* above the observed measures. Factor loadings and correlations between factors are shown in the figure as well. Factor loadings were high for all measures, ranging from .63 to .96. Correlations between factors were also large. The correlations between the word-reading and orthographic learning factors was .72 and .63 at Times 1 and 2, respectively.

Path analyses

To understand the longitudinal relations between word reading and orthographic learning, we constructed a baseline measurement model and three variations of an

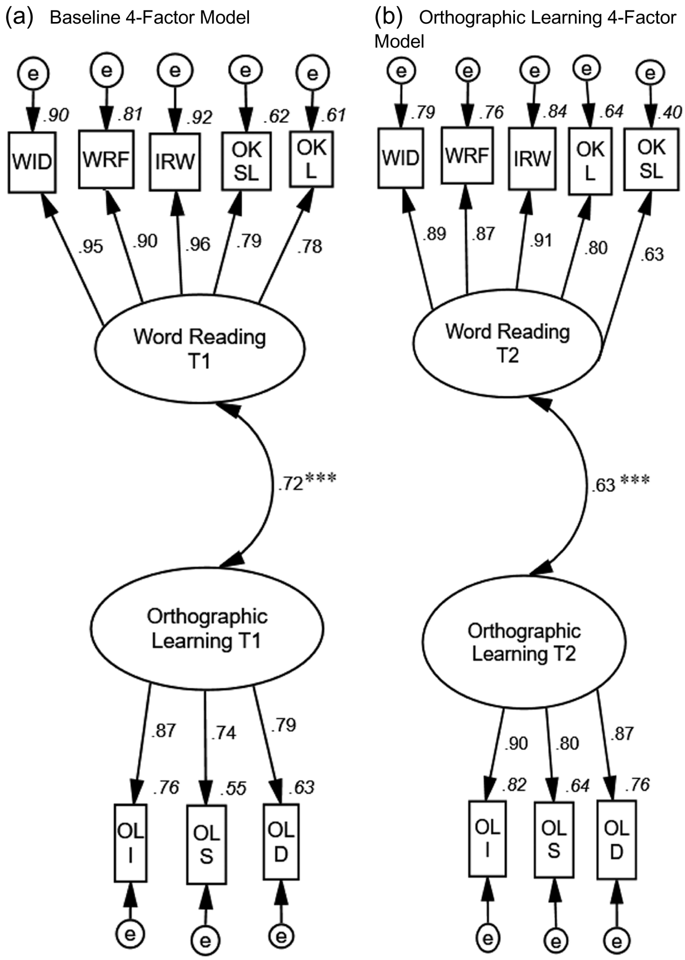

Figure 2. Factor models of word reading, orthographic knowledge, and orthographic learning measures at (a) Time 1 and (b) Time 2.
WID, word identification. WRF, word-reading fluency. IWR, irregular word reading. OK L, orthographic knowledge lexical. OK SL, orthographic knowledge sublexical. OL, orthographic learning. I, initial. S, spelling. D, delayed. $*p < .05$. $**p < .01$. $***p < .001$.

orthographic learning model. Two representative theoretical models are shown in Figure 3. The Time 1 and Time 2 factor models were used to construct the baseline measurement model. Measures of phonological awareness, nonverbal reasoning, and age in months were entered as control variables, and paths between these variables and the latent factors of word reading and orthographic learning at Time 1 were added. In addition, the control variables were set to correlate with one another. Autoregressor paths were added from orthographic

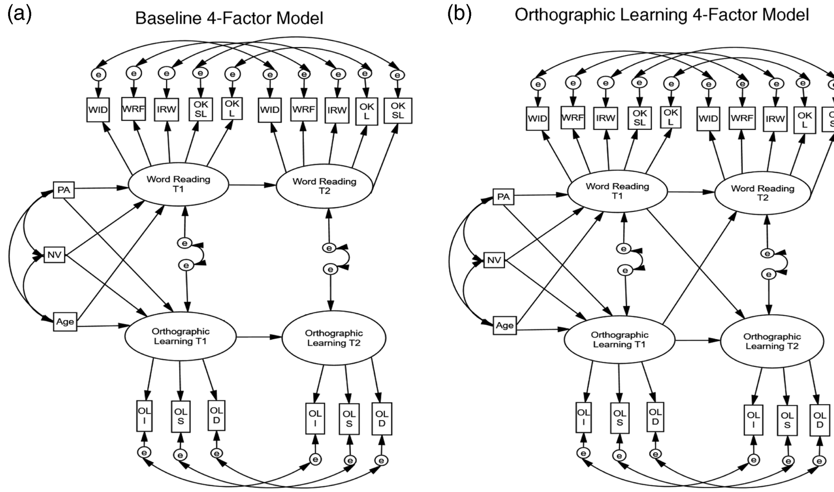

Figure 3. (a) Theoretical baseline and (b) orthographic learning models. WID, word identification.
WRF, word-reading fluency. IWR, irregular word reading. OK L, orthographic knowledge lexical. OK SL, orthographic knowledge sublexical. OL, orthographic learning. I, initial. S, spelling. D, delayed. T, Time. PA, phonological awareness. NV, nonverbal ability.

learning at Time 1 to Time 2, and from word reading at Time 1 to Time 2. The baseline model included correlated error variances from orthographic learning to word reading. Further, longitudinal residual covariances of the observed word-reading and orthographic measures were added. The baseline model did not include any paths from orthographic learning to word reading, and vice versa. For the variations of the orthographic learning model, cross-lagged paths between orthographic learning and word reading were added one at a time, in subsequent models, and compared against the baseline model to determined if the addition of one or both of the particular paths significantly improved model fit. Specifically, the path from word reading at Time 1 to orthographic learning at Time 2 was tested first, then from orthographic learning at Time 1 to word reading at Time 2, followed by a model with both cross-lagged paths.

Initially, we tested the longitudinal invariance of the baseline model following the recommendations outlined by Little (2013); we did so to support our claim that we measured the same constructs longitudinally. Constraints placed on T1 and T2 indicator loadings and intercepts of the same measures had little influence on CFI fit statistics. A change in CFI of .01 is sufficient to assume invariance of the constructs holds (Cheung & Rensvold, 2002; Little, 2013). This enabled us to proceed with examining and interpreting the path model. We proceeded to conduct the analysis; however, the standardized relationship between word-reading at Time 1 and Time 2 was larger than 1. As suggested by Little (2013), we restricted the path between word reading at T1 and T2 to unity (i.e., 1), to create an interpretable two time-point model.

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Next, we compared the influence of the cross-lagged paths between word reading and orthographic learning constructs on model fit. Fit statistics for the baseline model and the orthographic learning model are shown in the bottom portion of Table 3. The addition of a path from word reading to orthographic learning did not improve model fit. The addition of a path from orthographic learning to word reading did significantly improved model fit. Finally, the path that included both paths from (a) orthographic learning to word reading and (b) word reading to orthographic learning did not fit significantly better than that model with orthographic learning predicting word reading. Therefore, the orthographic learning model with a path from orthographic learning to word reading was the most parsimonious model, and thus retained as the preferred model and discussed below.

The orthographic learning model is shown in Figure 4 (see also Table 4 for coefficients). Age and phonological awareness were significant predictors of the word-reading factor at Time 1. In addition, age and phonological awareness were significantly related to the orthographic learning factor at Time 1. The relationship between Time 1 and Time 2 word reading was .91, $p < .001$, and the relationship between Time 1 and Time 2 orthographic learning was .61, $p < .001$. Error variances for word reading and orthographic learning at Time 1 were significantly related ($\beta = .60$, $p < .001$). Most important, orthographic learning at Time 1 was a significant predictor of word reading at Time 2 ($\beta = .10$, $p < .001$), after controlling for prior word-reading ability, phonological awareness, nonverbal reasoning, and age. Overall, 25% and 58% of the variance was accounted for in the orthographic learning factors at Time 1 and 2, respectively. In addition, 44% and 97% of the variance was account for in the word-reading factors at Time 1 and Time 2, respectively. Additional tables reporting the unstandardized estimates with mean structure and standard errors are reported in the online-only Supplemental Materials, conducted as per the recommendations of McDonald and Ho (2002).

As a final check on our results, we evaluated whether the nature of items in the sublexical orthographic knowledge task affected results. Specifically, this included items contrasting legal and illegal spellings, as well as those contrasting more and less frequent spellings. The latter are different from several prior studies. As such, we omitted the items that contrasted more or less frequent spellings and reconducted all analyses. We reran the factor, as well as the path, models to include the modified sublexical scores. Factor loadings for the modified task were .62 at Time 1 and .63 at Time 2. Model fit and all of the relations among constructs remained the same. Due to the little impact the modified sublexical task had on the models, we interpret the results with all the original items.

DISCUSSION

The goal of this study was to better understand which aspect of orthographic processing is involved in children's progress in learning to read words. To this end, we to examined the longitudinal relations between word-reading skills and orthographic learning and orthographic knowledge. We did so in a longitudinal

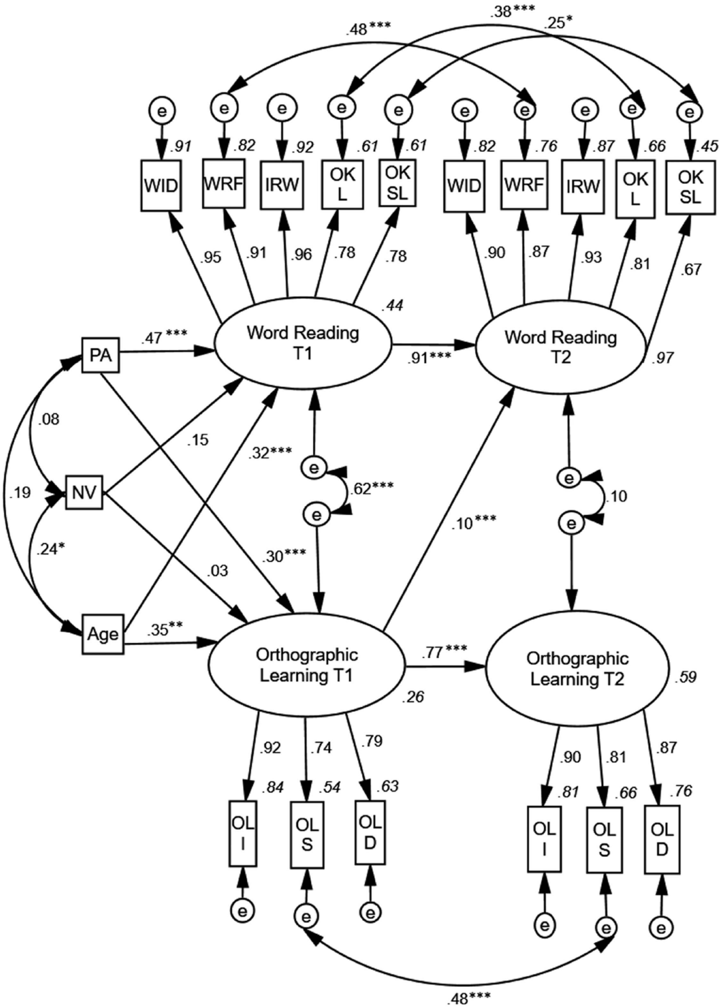

Figure 4. Four-factor path model predicting word reading with orthographic learning.
WID, word identification. WRF, word-reading fluency. IWR irregular word reading. OK L, orthographic knowledge lexical. OK SL, orthographic knowledge sublexical. OL, orthographic learning. I, initial. S, spelling. D, delayed. T, time. PA, phonological awareness. NV, nonverbal ability. *$p < .05$. **$p < .01$. ***$p < .001$.

study of a group of children initially tested in Grades 2 and 3 followed through to Grades 3 and 4, respectively. To evaluate orthographic learning, children independently read short stories containing novel words (based on Byrne et al., 2008), and learning was measured with immediate and delayed orthographic choice and spelling measures; these evaluated orthographic learning at the lexical level. In addition, children completed measures of lexical and sublexical orthographic knowledge, word-reading accuracy, word-reading efficiency, and irregular word reading. We first conducted CFA to evaluate the separability of orthographic learning and knowledge from word-reading itself (Burt, 2006; Castles & Nation, 2006). We then went on to model longitudinal relations between our identified orthographic factors and word reading.

Our CFA suggested a single word-reading factor, reflecting shared variance between the word-reading and orthographic knowledge measures, that is separable from orthographic learning. This was the best fitting and most parsimonious solution at Times 1 and 2. These findings provide some of the strongest evidence to date for orthographic learning as a distinctive factor in the word-reading process; the results of the factor analyses indicated that this process is related to, but separable from, word reading. As such, the results are consistent with Share's (1995, 2011) proposal of a distinct, measurable skill representing the child's dynamic orthographic learning ability.

In terms of orthographic knowledge, our findings consolidate the view of orthographic knowledge as reflecting the child's crystallized *store* of orthographic representations; this work provides much-needed empirical clarity in a field rife with debate as to the nature of the orthographic knowledge construct (see, e.g., Wagner & Barker, 1994). Measures of lexical and sublexical orthographic knowledge appears to reflect this store to such an extent that its measurement is statistically indistinguishable from word reading itself, at least in our sample of English-speaking children in Grades 2 to 4. We do note that, of all of the measures, sublexical orthographic knowledge had the lowest factor loadings; it is possible that analyses in other studies might identify this as a separable factor, perhaps earlier in development. That said, findings from the present study point to a single word-reading factor, across both lexical and sublexical levels of orthographic knowledge and diverse aspects of word reading, one that is separable from orthographic learning. Prior studies have shown that performance on orthographic knowledge tasks load on a single factor that is separable from phonological awareness; in these studies, this factor is shown to be correlated with word reading (e.g., Hagiliassis, Pratt, & Johnston, 2006). Our findings suggest that this correlation is so high as to reflect a single factor. This finding might help to explain the mixed pattern of results in prior studies evaluating the relation between orthographic knowledge and word reading; some have shown that orthographic knowledge is a predictor of gains in word reading (Cunningham et al., 2001; Wagner & Barker, 1994), while others have shown that orthographic knowledge is an outcome of word reading (e.g., Conrad & Deacon, 2016; Deacon et al., 2012). This mixed set of results has emerged in studies using linear regression analyses, treating variables separately. In applying CFA, we have found that one solution to this mixed set of results is that tasks assessing orthographic knowledge might not index a construct that extends beyond any word-reading skill itself. This finding supports suggestions that using static measures to explore relations between orthographic processing and word reading may result in circularity, as the two measures appear to be tapping one and the same thing (Burt, 2006; Castles & Nation, 2006).

Our structural equation modeling revealed that orthographic learning supported word-reading development. We found that orthographic learning at Time 1 was related to word reading at Time 2, after controlling for Time 1 word reading; effectively, these results support the conclusion that orthographic learning determines the progress that children make in learning to read words accurately over the course of 1 year. These findings extend prior studies demonstrating a relation between orthographic learning and measures of word reading concurrently (e.g., Ricketts et al., 2011). Most important, these results are a novel confirmation of the theoretical predictions of the power of orthographic learning in setting the pace for children's acquisition of word-reading skills (e.g., Share, 2007). Further, these relations persist beyond controls for phonological awareness and nonverbal reasoning, and they emerge in structural equation modeling that reduces the impact of measurement error. Based on these findings, we suggest that dynamic orthographic learning capacity, rather than static orthographic knowledge, may be a specific component of orthographic processing that is responsible for word-reading development (e.g., Share, 2007).

We did not find relations in the other direction; word-reading skills did not contribute significantly to individual differences in gains in orthographic learning skills. A model that included this path did not fit significantly better than a model without this path, and this path did not emerge as significant in either model. These findings counter the suggestion that children's word-reading skills might set the pace for the development of their skills in learning new orthographic forms (e.g., Wolter et al., 2011). The absence of a significant contribution of word-reading skills to gains in orthographic learning is perhaps surprising given widespread evidence of Matthew effects, with good word readers making more subsequent gains in word reading (Stanovich, 1986); orthographic learning could have been a candidate mechanism for these effects. Yet our findings suggest that word-reading skills might not promote orthographic learning skills directly. Given these results and following on earlier work (e.g., Moll & Bus, 2011), we speculate that stronger word-reading skills leads to increased reading exposure, rather than increased orthographic learning skills; it is this increased reading exposure that provides more opportunities for orthographic learning to occur, thereby enabling word-reading development. Such speculations need empirical testing.

Other limitations could be addressed in further studies. A first lies in measurement. In terms of orthographic learning, we used a measure of individual differences as they occur in naturalist reading (Byrne et al., 2008). Following on this work, we provided the correct pronunciation in cases in which the child was not able to read the target word, primarily to reduce the effects of phonological decoding on results. Other orthographic learning studies have typically not provided the pronunciation of the word (Share, 2007); manipulating this variable would be a useful empirical extension (see, e.g., Tucker, Castles, Laroche, & Deacon, 2016). Similarly, it would be useful to examine the extent to which children's orthographic learning might differ based on the context in which it occurs (e.g., manipulating the explicitness of instruction and the degree to which the context is naturalistic; e.g., Share, 2008). Second, to reduce the possibility that relations uncovered were due to a single specific task format, we included more than one assessment of orthographic learning and knowledge (see, e.g., Deacon et al., 2012; Ouellette & Fraser, 2009; Ricketts et al., 2011; Share, 2007; Wang et al., 2013). Nevertheless, other measures of each of these constructs might be useful, particularly outcomes such as latency, assessed naming, and lexical decision tasks. It might also be useful to further explore potential differences in orthographic knowledge items contrasting legality versus frequency; our own analyses did not point to such differences, but these might emerge, potentially reflecting a continuum of orthographic knowledge skill. Similarly, some theorists have included rimes, syllables, and morphemes as equivalent units within orthographic knowledge (e.g., Ehri, 2005); it remains to be confirmed empirically if this is the case. In addition, the reliability of orthographic learning, immediate and delayed, was relatively low, albeit acceptable for an experimental measure. Although we were still able to reveal significant relations, a stronger pattern of effects might be demonstrated with more reliable measures. In terms of sample, we combined two grades of children, a decision confirmed by the absence of interactions with grades. It would be useful to examine this pattern of results with larger groups of children. Taken together, we suggest that these findings need to be confirmed with other measures of orthographic learning and knowledge and with other age ranges.

To conclude, the present study provides insight into the separability of different components of the broad construct of "orthographic processing" and their association with word reading. We demonstrate that the dynamic skill of orthographic learning, but not the crystalized body of orthographic knowledge, is separable

Table 4. *Coefficients from orthographic learning structural equation model*

	Unstandardized coefficient	Standard error	Standardized coefficient
	Orthographic learning T1		
Age (months)	0.136	.035	.351***
Nonverbal reasoning	0.216	.070	.301**
Phonological awareness	0.013	.043	.029
	Word reading T1		
Age (months)	0.490	.124	.324***
Nonverbal reasoning	0.262	.142	.151
Phonological awareness	1.314	.230	.467***
	Orthographic learning T2		
Orthographic learning T1	0.693	.082	.769***
	Word reading T2		
Word reading T1	1.000	—	.912***
Orthographic learning T1	0.418	.097	.097***

Note: T1, Time 1. T2, Time 2. *$p < .05$. **$p < .01$. ***$p < .001$.

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from children's word reading. The skull of orthographic learning is also related to the development of word-reading skills. These findings suggest that there is a separate orthographic component to the development of children's word reading, as proposed within the Self-Teaching Hypothesis (Share, 1995, 2011). This orthographic learning component can be captured by a dynamic orthographic learning measure and is related to the development of word-reading skills in English-speaking children in the middle elementary school years.

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SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/S0142716418000681

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