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Paired-associate learning ability accounts for unique variance in orthographic learning

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Abstract

Paired-associate learning is a dynamic measure of the ability to form new links between two items. This study aimed to investigate whether paired-associate learning ability is associated with success in orthographic learning, and if so, whether it accounts for unique variance beyond phonological decoding ability and orthographic knowledge. A group of 63 children aged 8-10 completed an orthographic learning task and three types of paired-associate learning task: visual-visual, visual-verbal, and verbal-verbal. The results showed that both visual-verbal and verbal-verbal (but not visual-visual) paired-associate learning ability were associated with success in learning the spellings of novel words. Moreover, hierarchical regression analyses showed that visual-verbal paired-associate learning predicted orthographic learning even after phonological decoding skill and existing orthographic knowledge had been accounted for. We propose that paired-associate learning ability may be one of the underlying mechanisms of orthographic learning, facilitating the connection between the phonology and orthographic representation of a word.

At the heart of orthographic learning is the acquisition of rich, high quality lexical representations of written words, whose rapid access is essential for fluent reading (Castles & Nation, 2006; Nation & Castles, in press). The aim of this study was to examine the relationship between a dynamic learning measure – paired-associate learning – and the ability to establish novel orthographic representations. Although many studies have reported a link between paired-associate learning and reading ability (Gascon & Goodglass, 1970; Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Litt, de Jong, van Bergen, & Nation, 2013; Litt & Nation, 2014; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Messbauer & Jong, 2006; Vellutino, Bentley, & Phillips, 1978; Vellutino, Steger, Harding, & Phillips, 1975; Wang, Nickels, & Castles, 2015; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001), this is the first study to examine whether this link extends to the process of acquisition of orthographic representations themselves.

Previous research on predictors of successful orthographic learning has focussed on two key factors: phonological decoding and existing orthographic knowledge. Phonological decoding is thought to be the first and primary factor in orthographic learning, as described in the influential self-teaching hypothesis (Share, 1995, 2008). The process of phonologically decoding an unfamiliar word may draw the reader's attention to the individual letters of a word and also allow them to generate its phonology, supporting the establishment of links between orthographic and phonological representations. In support of this, several studies have reported an association between phonological decoding and orthographic learning performance (Cunningham, 2006; Cunningham, Perry, Stanovich, & Share, 2002; Nation, Angell, & Castles, 2007; Wang, Castles, & Nickels, 2012; Wang, Nickels, Nation, & Castles, 2013), and compromised phonological decoding skill has been associated with impaired orthographic learning (Ehri & Saltmarsh, 1995; Manis, 1985; Reitsma, 1983; Share & Shalev, 2004).

In addition to phonological decoding, a child's existing orthographic knowledge has been found to be a strong predictor of orthographic learning, and this is true for both typically developing readers (Conners, Loveall, Moore, Hume, & Maddox, 2011; Cunningham, 2006; Cunningham et al., 2002) and children with reading difficulties (Wang, Marinus, Nickels, & Castles, 2014). In these studies, children's existing orthographic knowledge has been measured using a range of tasks including: distinguishing the correct spelling of a word from a pseudohomophone (e.g., *sleep – sleap*); choosing between nonwords with letter combinations that are common in English spelling paired with their psuedohomophone containing an unusual English spelling (e.g.,*fage – fayj*, 'which one looks more like a real word'?); or reading aloud irregular words such as *yacht,* since accuracy here requires word-specific orthographic knowledge. For all of these measures, the level of orthographic knowledge consistently predicts success in orthographic learning even after phonological decoding skill is controlled for.

Beyond these phonological and orthographic sources of knowledge, what may be also crucial for orthographic learning is the ability to form links between them. According to Ehri's phase theory of sight word learning (Ehri & Saltmarsh, 1995; Ehri, 2005), the ability to form detailed connections between visual and phonological forms of words is the foundation for building up a consolidated sight word vocabulary. This way, seeing the written form of a word provides rapid and automatic information about its phonology (and meaning) in support of fluent reading comprehension. Therefore, a child's basic ability to learn connections between two items, that is, paired-associate learning ability, seems a likely candidate for contributing to success in orthographic learning.

Paired associate learning ability is typically measured by tasks that involve presenting sets of pairs of items to be learned. The items may be presented within one modality (e.g. two visual objects, or two spoken words), or they may be cross-modal (e.g., visual object with a spoken word). Importantly, the links to be formed are new and arbitrary, with learning being tested by subsequently presenting one item of the pair and requiring participants to identify the other one (e.g., Vellutino et al., 1975).

As noted, it is well established that there is a positive association between paired-associate learning ability and reading ability. In addition, children with dyslexia have been found to have more difficulty learning these associations than typically-developing readers (Litt & Nation, 2014; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Messbauer & Jong, 2006; Vellutino et al., 1978, 1975; Wang et al., 2015). Studies have also found that adults with dyslexia show abnormal neural processing in mechanisms associated with print-to-sound integration (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009).

More importantly, previous studies have found that paired-associate learning ability accounts for reading performance even after phonological skills have been controlled for, suggesting it may tap a separate mechanism to phonological decoding involved in learning to read (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Notably, Hulme et al. (2007) found that visual-verbal paired-associate learning ability independently predicted irregular word reading but not nonword reading. Given that irregular words cannot be read correctly by phonological decoding alone, this suggests that paired-associate learning ability may be particularly associated with the formation of orthographic representations or their links with phonology. However no study to date has directly examined the association between paired-associated learning ability and children's acquisition of new orthographic representations.

Although there is strong evidence for a connection between paired-associate learning ability and reading, it is less clear which kinds of paired-associations have the strongest link. Hulme et al (2007) used three different types of paired-associate learning task – visual-visual, visual-verbal and verbal-verbal. They found that only visual-verbal paired-associate learning was associated with children's reading after phonemic awareness was controlled for. Hulme et al (2007) therefore suggested that it is cross modal visual-verbal paired-associate learning that may play a unique role in reading development.

However, the findings of other studies suggest that the relationship between paired-associate learning and reading ability does not arise from the cross-modal association but may lie in the verbal aspects of the task (e.g., Elbro & Jensen, 2005; Litt et al., 2013; Litt & Nation, 2014; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Messbauer & Jong, 2006). Elbro and Jensen (2005) found that children with dyslexia were poorer at learning associations between pictures and nonwords than controls, but their performance was as good as controls when the verbal stimuli were familiar words. More recently, Litt and colleagues (Litt et al., 2013; Litt & Nation, 2014) included a paired-associate learning task involving verbal learning but not verbal production (verbal-visual paired-associate learning) and found that in typically developing children, only tasks involving verbal production (verbal-verbal, visual-verbal paired-associate learning) predicted reading ability, and that the impairments in children with dyslexia were similarly restricted to these tasks.

In summary, paired-associate learning ability has been linked with various measures of reading success, but the nature of this link, and the cognitive capacities that underlie it, remain unclear (see also Byrne et al., 2013). As well, although there is a strong case to be made that the ability to learn paired-associations may independently predict success in orthographic learning, no study to our knowledge has directly tested this prediction: Previous studies have examined various kinds of existing reading skills rather than the dynamic ability to acquire new orthographic representations. Testing this prediction requires extending research on paired-associate learning to exploring its association with the orthographic learning process itself.

Current Study

The aim of this study was to investigate, for the first time, whether paired-associate learning ability contributes to success in orthographic learning, and if so, whether it accounts for unique variance in orthographic learning over and above phonological decoding ability and orthographic knowledge. In addition, following Hulme et al., (2007) we aimed to explore whether the ability to acquire word-specific orthographic representations was related specifically to learning associations between visual and verbal forms or to a more general associative learning process. To this end, we employed three different kinds of paired-associate learning task: visual-verbal, visual-visual, and verbal-verbal.

Finally, we also included a context manipulation in the orthographic learning task: children were presented with novel written words (e.g. *cleep*) either in a story context or embedded in a list of familiar words. This allowed us to examine whether any relationship observed between paired-associate learning and orthographic learning is attributable to task similarity. In orthographic learning tasks without context, learning the novel words could be seen as essentially a form of paired-associate learning (although the pairing of the stimuli is arbitrary in the paired-associate learning task but not in the orthographic learning task). On the other hand, when orthographic learning takes place in a story context, learning is more natural and the text provides syntactic and semantic information about the novel word (Landi, Perfetti, Bolger, Dunlap, & Foorman, 2006; Martin-Chang & Levy, 2005; Wang, Castles, Nickels, & Nation, 2011; Tunmer & Chapman, 1998). Therefore, evidence for an association between paired-associate learning ability and orthographic learning in context would provide stronger and more ecologically valid evidence for the significance of this ability in children's typical reading acquisition than would an association only in the condition without context.

Method

Participants

A total of 65 Grade 3-4 children in the age range 8;6-10;3 years (mean age: 9 years 5 months; 37 girls) participated in this study. Some of the children (43) were recruited from three mainstream primary schools in the Central Coast Region north of Sydney, Australia. These children were tested in quiet rooms at their schools. The remaining 22 children were recruited from advertisements and were tested at Macquarie University. All participants were tested individually and completed the tasks in two one-hour sessions as part of a more extensive test battery. The two sessions were completed on separate days (approximately a week to two weeks apart). All children had normal hearing, normal or corrected vision and no known learning disabilities. Two children were excluded from the analyses because they did not attend the second test session, leaving a total of 63 children's data in the analyses.

Materials and Procedure

Orthographic Learning. The design and procedure of this task were identical to those of Wang et al., (2015; originally adapted from Byrne et al., 2008). A total of 16 target items, all 4-6 letter nonwords, were used. The items had regular letter-sound mappings according to Rastle and Coltheart (2000). The items all had inconsistent spellings (e.g., /klip/ can be spelled as *clepe, cleap, kleep*), hence, word specific orthographic knowledge was required to spell them correctly.

Eight of the nonwords were presented in short stories, with each repeated four times in the story (Context condition). The stories averaged 23 words in length each and started with the sentence 'The new word is ____', followed by a story containing the novel word three more times (e.g., *There is a hairy monster called a smope. The smope is very big. If you see a smope, you should run away*). The other eight novel words were presented in word lists rather than in stories (No Context condition). The filler words were the (non-target) words used in the Context condition scrambled across all eight stories. Both conditions begin with the sentence "the new word is ___" to highlight the novel word to be learned.

When presented with the target items, the child was instructed to read the stories (Context condition) or word lists (No Context condition) together with the experimenter and to take over reading aloud every time the experimenter stopped. The children read on average 9 words from each story or list, including all 4 target words. This adaptation of the common orthographic learning set up (i.e., having the children read the entire story themselves) was made to ensure that the reading task was not too taxing or time consuming for any child, but still allowed them to decode the novel words by themselves.

Orthographic learning was assessed by a spelling task and followed by an orthographic choice task. However, there were ceiling effects in the orthographic choice task, with 25 out of 63 children obtaining a perfect score, and another 22 making only one error. For this reason, we report data for the spelling task only. Following Byrne et al (2008), the spelling task was carried out immediately after exposure to four test items. That is, the child was exposed to items 1-4, and immediately after that, he or she was asked to spell those four target items. This procedure was then repeated for target items 5-8. The same procedure was repeated in the second session for the other 8 items. The order of the presenting the items was counterbalanced. During the spelling task, the children were instructed to write down each of the new words that the experimenter said aloud, exactly as they appeared in the stories or list of words. The first sentence of the stories or word lists served as a prompt (e.g. Context condition: “There is a kind of boat called a laif. Write laif.”; No Context condition: “The new word is vaid. Write vaid.”). Accuracy for every word was scored as 1 or 0.

Paired-associate learning (PAL). Three types of PAL task were used: visual-visual; visual-verbal, and verbal-verbal (adapted from Hulme et al., 2007). The visual-visual and the verbal-verbal conditions were carried out in the same session whereas the visual-verbal condition was carried out in the second test session. The procedure of the tasks was identical to Hulme et al. (2007) except that we employed five learning trials instead of six to avoid potential ceiling effects, as our participants were older on average than theirs.

Visual – visual PAL. Here, children were asked to learn pairings between two shapes. There were two sets of eight-point shapes taken from Vanderplas and Garvin (1959), printed in black. Each set had four shapes and a different background colour.

First, one set of four cards with shapes was laid out in a row in front of the child, then the experimenter held a second set of four cards with different shapes and placed each one next to its pair in the first set of cards. When the two shapes were placed adjacent to each other, the experimenter said ‘this shape goes with this shape’. The two cards remained adjacent for 5 seconds, and then the experimenter removed the card from the second set and placed the next card with the same procedure. After all four pairs were introduced, the experimenter shuffled the second set of cards and asked the child, one card at a time, ‘which shape goes with this shape?’ The child was asked to point to the correct match from the first set of cards to be scored as correct. The experimenter recorded the responses and feedback was given. This procedure was repeated five times, making a total of 20 responses.

Visual – verbal PAL. In this task, the child was asked to learn pairings between shapes and spoken nonsense words. The shapes were made in the same way as the ones in the visual-visual PAL condition. The nonsense words were selected from the Diagnostic Spelling Test (Kohnen, Nickels, & Castles, 2009) and consisted of three-phonemes of the consonant-vowel-consonant type, although in some cases they would contain complex consonant clusters if spelled according to English sound-letter rules. During the task, the experimenter first asked the child to repeat the four nonwords used in the task (*leet, zorm, heg, nam*) in order to make sure that the child was able to pronounce the words. The experimenter held a set of four cards with shapes (that were different from the shapes used in the visual-visual PAL), showed the child one card at a time and said the associations twice. For example, ‘This shape goes with *leet*, [2-s interval], This shape goes with *zorm*.’ After all four pairs were introduced, the experimenter held one card at a time and asked the child ‘which nonsense word goes with this shape?’ The experimenter recorded the responses and feedback was given in each trial. This procedure was also repeated five times, making a total of 20 responses.

Verbal – verbal PAL. In this task, the child was asked to pairings between spoken nonsense words using two sets of four stimuli. First the child was asked to repeat the eight nonsense words (*vack, darp, lurth, hud; yoom, neeg, tem, pog*). The experimenter then said the associations twice e.g., '*darp* goes with *tem*', [2-s interval], '*darp* goes with *tem*'. After all pairs were introduced, the child was asked 'which nonsense word goes with *darp*?' Responses were recorded by the experimenter and feedback was provided. The procedure was repeated five times, making a total of 20 responses.

Reading and cognitive ability assessments.

Orthographic knowledge. Existing orthographic knowledge was indexed by irregular word reading ability. The children were asked to read 30 irregular words aloud from a subset of the Coltheart & Leahy test (Coltheart & Leahy, 1996). The words were presented on a lap top screen one at a time. The reliability of the test was high, with Cronbrach's $\alpha = .85$.

Phonological decoding. Phonological decoding ability was indexed by nonword reading. The children were asked to read 30 nonwords words aloud from a subset of the Coltheart & Leahy test (Coltheart & Leahy, 1996). The words were presented on a 14 inch laptop screen. The reliability of the test was high, with Cronbrach's $\alpha = .92$.

Nonverbal intelligence. Nonverbal IQ was assessed with the Matrices Subtest of the Wechsler Nonverbal Scale of Ability (Wechsler, 2006).

Results

Table 1 summarises results for all the measures. There was a significant main effect of PAL task, $F(2, 187) = 28.20, p < .01$, with visual-visual PAL scores being higher than those for visual-verbal PAL, $t(63) = 3.78, p < .01$, which were in turn higher than those for verbal-verbal PAL, $t(63) = 5.36, p < .01$. For the orthographic learning task, spelling performance in the Context condition was significantly better than in the No Context condition, $t(63) = 2.91, p = .01$.

Table 1. Means and Standard Deviation of the Measures.

	M	SD
Age	9.46	0.37
Nonverbal IQ (standard score, mean=100)	108.58	11.84
Orthographic knowledge		
Irregular word reading accuracy (/30)	21.58	4.07
Phonological decoding		
Nonword reading accuracy (/30)	22.52	6.68
Paired-associate learning		
Visual-visual (/20)	14.57	3.94
Visual-verbal (/20)	11.91	5.05
Verbal-verbal (/20)	8.23	5.85
Orthographic learning (Spelling)		
Context (/8)	5.73	2.10
No Context (/8)	5.12	2.29

To investigate how well PAL, phonological decoding ability, and orthographic knowledge predict successful orthographic learning, we conducted a set of correlational analyses followed by multiple hierarchical regressions. The outcome measures were orthographic learning scores as measured by spelling.

Table 2 shows the results of correlations and partial correlations, controlling for non-verbal IQ, between spelling and its predictors, in both the Context and No Context conditions. The correlations with and without controlling for nonverbal IQ showed the same pattern. Similarly, the correlations for the Context and No Context conditions and their predictors also showed the same pattern, with no significant differences in the correlation coefficients.

For both the Context and No Context conditions, we found that orthographic learning was significantly correlated with visual-verbal PAL, and verbal-verbal PAL but not with visual-visual PAL. Learning success was also significantly correlated with phonological decoding (measured by nonword reading), and orthographic knowledge (measured by irregular word reading).

A series of hierarchical regression analyses was conducted to further explore these correlations, and to examine whether the various PAL abilities predicted orthographic learning after phonological decoding skill and orthographic knowledge had been accounted for. The analyses were conducted separately for orthographic learning in the Context and No Context conditions. In Step 1, nonverbal IQ and phonological decoding performance were entered to the regression models, followed by orthographic knowledge at Step 2, and finally the three sets of PAL scores respectively in separate models, at Step 3. The results of the regression analyses are summarized in Tables 3 and 4.

At Step 1, for both the Context and No Context conditions, orthographic learning performance was significantly predicted by phonological decoding skill. At Step 2, when both phonological decoding skill and orthographic knowledge were included in the model, both significantly predicted orthographic learning. When the PAL scores were added at Step 3, visual-verbal PAL significantly predicted orthographic learning over and above phonological decoding and orthographic knowledge in both Context and No Context learning conditions. Visual-verbal PAL also significantly improved the model fit in both conditions, as indexed by a significant r^2 change. In contrast, the models with verbal-verbal PAL and visual-visual PAL did not account for additional variance in orthographic learning at Step 3 in either condition, and the r^2 changes also did not reach significance.

An additional analysis was conducted to further test whether visual-verbal PAL was a significantly better predictor of orthographic learning than verbal-verbal and visual-visual PAL as suggested from the results of the regression models. We estimated the 95% confidence intervals via bias corrected bootstrap (1,000 re-samples) of the standardized beta values. Comparing between visual-verbal and verbal-verbal PAL, the confidence intervals overlapped by less than 50% in the Context condition, suggesting that the two beta values (.32 vs. .00) are significantly different from each other ($p < .05$; Cumming, 2009). However, the confidence intervals overlapped by more than 50% in the No Context condition, suggesting that the two beta values (.26 vs. .18) are not significantly different from each other. Therefore, visual-verbal PAL was a significantly better predictor than verbal-verbal PAL, but only when orthographic learning took place in context. Comparing between visual-verbal and visual-visual PAL, the confidence intervals overlapped by less than 50% in both conditions, suggesting that visual-verbal PAL was a significantly better predictor than visual-visual PAL.

Table 2

Correlations of the orthographic learning outcome measures and the predictors with (above the diagonal line) and without (below the diagonal line) age and nonverbal IQ controlled.

	Orthographic learning		**Predictors**				
	Orth. learning: Context[1]	Orth. Learning: No Context[2]	Visual-Visual PAL	Visual-Verbal PAL	Verbal-Verbal PAL	Phonological decoding ability[3]	Orthographic knowledge[4]
Orth. learning: Context[1]	-	**.70****	.15	**.58****	**.41****	**.62****	**.64****
Orth. Learning: No Context[2]	**.72****	-	.14	**.45****	**.50****	**.52****	**.59****
Visual-Visual PAL	.22	.23	-	.18	.20	.10	**.31***
Visual-Verbal PAL	**.61****	**.49****	.26	-	**.50****	**.40****	**.40****
Verbal-Verbal PAL	**.42****	**.50****	.22	**.51****	-	**.51****	**.52****
Phonological decoding ability[3]	**.65****	**.58****	.22	**.46****	**.50****	-	**.69****
Orthographic knowledge[4]	**.67****	**.64****	**.41****	**.46****	**.51****	.75**	-
NonVerbal IQ[5]	.26	**.30***	**.34***	.27	.09	**.41****.	**43****

1. Orthographic learning in Context condition: assessed by a spelling task; 2. Orthographic learning in No Context condition: assessed by a spelling task; 3. Phonological decoding ability: assessed by nonword reading; 4. Orthographic knowledge: assessed by irregular word reading; 5. Nonverbal IQ: assessed by the Wechsler Nonverbal Scale of Ability.

** p < .01; * p < .05

Table 3.

Outcomes of the hierarchical regression analyses for orthographic learning in the Context Condition

Models	**Variables**	**R**	**Adj. R^2**	**ΔR^2**	**B**	**SE**	**Beta**	**t**
1	*Step 1*	.72	.50	-				
	Nonverbal IQ				.01	.02	.03	0.27
	Phonological decoding				.20	.03	**.70****	6.76
2	*Step 2*	.77	.58	**.08****				
	Nonverbal IQ				-.01	.02	-.04	-0.41
	Phonological decoding				.12	.04	**.41****	3.22
	Orthographic knowledge				.18	.05	**.44****	3.45
3	*Step 3*	.78	.58	.01				
	Nonverbal IQ				.00	.02	-.01	-0.13
	Phonological decoding				.12	.04	**.40****	3.11
	Orthographic knowledge				.19	.05	**.47****	3.64
	Visual-Visual PAL				-.06	.05	-.11	-1.17
4	*Step 3*	.82	.64	**.07****				
	Nonverbal IQ				-.01	.02	-.08	-0.85
	Phonological decoding				.09	.04	**.32****	2.69
	Orthographic knowledge				.15	.05	**.36****	3.00
	Visual-Verbal PAL				.14	.04	**.32****	3.42
5	*Step 3*	.73	.50	.02				
	Nonverbal IQ				-.01	.02	-.04	-0.40
	Phonological decoding				.12	.04	**.41****	3.08
	Orthographic knowledge				.18	.06	**.44****	3.28
	Verbal-Verbal PAL				.00	.04	.00	0.01

The dependent variable was orthographic learning in Context measured by spelling, and the predictor variables were paired-associate learning, phonological decoding, orthographic knowledge, and nonverbal IQ. Three different types of paired-associate learning were analysed in three separate sets of models.

** indicates $p < .01$; * indicates $p < .05$.

Table 4.

Outcomes of the hierarchical regression analyses for orthographic learning in the No Context Condition

Models	Variables	R	Adj. R^2	ΔR^2	B	SE	Beta	t
1	*Step 1*	.66	.42	-				
	Nonverbal IQ				.02	.02	.10	0.88
	Phonological decoding				.20	.04	**.61****	5.50
2	*Step 2*	.71	.48	**.07****				
	Nonverbal IQ				.01	.02	.04	0.42
	Phonological decoding				.11	.05	**.34***	2.42
	Orthographic knowledge				.18	.06	**.40****	2.89
3	*Step 3*	.71	.47	.00				
	Nonverbal IQ				.01	.02	.04	0.34
	Phonological decoding				.11	.05	**.34***	2.41
	Orthographic knowledge				.18	.06	**.39****	2.75
	Visual-Visual PAL				.01	.06	.02	0.23
4	*Step 3*	.74	.52	**.05***				
	Nonverbal IQ				.01	.02	.03	0.29
	Phonological decoding				.09	.05	.27	1.97
	Orthographic knowledge				.14	.06	**.31***	2.28
	Visual-Verbal PAL				.12	.05	**.26***	2.44
5	*Step 3*	.73	.50	.02				
	Nonverbal IQ				.01	.02	.05	0.49
	Phonological decoding				.09	.05	.28	1.94
	Orthographic knowledge				.16	.06	**.34***	2.47
	Verbal-Verbal PAL				.08	.05	.18	1.69

The dependent variable was orthographic learning in No Context measured by spelling, and the predictor variables were paired-associate learning, phonological decoding, orthographic knowledge, and nonverbal IQ. Three different types of paired-associate learning were analysed in three separate sets of models.

** indicates $p < .01$; * indicates $p < .05$.

Discussion

This study aimed to uncover the factors that might be important for successful orthographic learning, a crucial skill in reading development. In particular, we aimed to discover whether paired-associate learning ability was associated with orthographic learning over and beyond phonological decoding ability and orthographic knowledge, which are both well-known predictors of successful orthographic learning. We included three types of paired-associate learning task: visual-verbal, visual-visual and verbal-verbal, to better understand the nature of any relationships observed. Orthographic learning also took place either with or without a meaningful sentence context. The manipulation of context allowed us to investigate whether the relationship between paired-associate learning and orthographic learning extends to naturalistic reading situations.

In the correlational analyses, we found that both visual-verbal and verbal-verbal paired-associate learning ability were highly associated with success in orthographic learning. This was the case regardless of whether the novel words were learned in lists or in stories, demonstrating that the relationship between paired-associate learning and orthographic learning can be extended to a naturalistic reading environment. In contrast, visual-visual paired-associate learning showed no association at all with learning success. These results are consistent with the findings of several previous studies that have used static reading measures, and strongly indicate that the relationship between paired-associate learning and reading is not driven by general associative learning ability, but rather appears to be specific to the formation of links that involve verbal material (Elbro & Jensen, 2005; Litt et al., 2013; Litt & Nation, 2014; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Messbauer & Jong, 2006).

Notably, in the hierarchical regression analyses visual-verbal paired-association ability was found to predict orthographic learning even after phonological decoding ability and orthographic knowledge had been accounted for. In contrast, verbal-verbal paired-associate learning did not account for additional variance in orthographic learning after these strong predictors had been controlled. These findings are consistent with those of Hulme et al., (2007) in suggesting a strong relationship between cross-modal paired-associate learning and the orthographic aspects of reading. They also fit well within Ehri's phase theory of sight word learning (Ehri & Saltmarsh, 1995; Ehri, 2005), where the establishment of connections between visual and phonological forms of words is the foundation for sight word acquisition. Importantly, the present results provide the first evidence for a unique contribution of visual-verbal paired-associate learning to the dynamic process of acquiring new orthographic representations.

The finding of stronger association between visual-verbal paired-associate learning and orthographic learning than verbal-verbal paired-associate learning contrasts somewhat with the results of recent studies suggesting that it is the verbal output component of paired-associate learning that is particularly associated with reading (Litt et al., 2013; Litt & Nation, 2014). It is important to note, however, that the outcome measures used in these previous studies were quite different from ours: Litt and colleagues measured reading accuracy while we measured the acquisition of spellings of novel words. The former requires verbal output, which might be more strongly associated with the verbal aspects of reading such as phonological decoding that we controlled for. On the other hand, visual-verbal cross-modal learning abilities may contribute uniquely to the initial stages of learning a novel written word: when seeing a word for the first time, particular attention may be drawn to processing its visual features (letters) and linking them with phonology.

It is important to note that although visual-verbal (and not verbal-verbal) paired-associate learning uniquely predicted orthographic learning both with and without context, the differences in the associations between visual-verbal and verbal-verbal paired-associate learning only reached significance when orthographic learning took place in context. Therefore, the findings should be interpreted with some caution. Further examination of the acquisition of the different components of orthographic learning (i.e., the verbal and visual forms), as well as the associative mechanism itself, may shed light on how each relates to orthographic learning and why this may differ somewhat across different learning contexts.

Based on these findings, we will now discuss in more detail why and how paired-associate learning might contribute to successful orthographic learning. It is important to first consider why phonological decoding, orthographic knowledge and visual-verbal paired-associate learning ability might each account for unique variance in orthographic learning ability. Consistent with previous studies examining phonological decoding and orthographic learning (Bowey & Miller, 2007; Cunningham et al., 2002; Kyte & Johnson, 2006; Wang et al., 2013), we found that phonological decoding skill was a strong predictor of orthographic learning. These results are in line with Share's self-teaching hypothesis (Share, 1995, 1999), in which phonological decoding is described as the *sine qua non* of orthographic learning, allowing the child to construct the phonology of novel printed words and link them with words in oral vocabulary.

Also consistent with previous studies, we found that existing orthographic knowledge as indexed by irregular word reading ability predicted orthographic learning (Conners et al., 2011; Cunningham, 2006; Cunningham et al., 2002; Wang et al., 2013), and as a predictor accounted for as much variance as phonological decoding skill. However, the basis of this association is less clear than in the case of phonological decoding. It could simply be the fact that existing orthographic knowledge indexes a child's past success in orthographic learning (tapping a range of skills including possibly paired-associate learning ability) and so is a good predictor of future learning. Alternatively, it could be that orthographic knowledge is actively drawn on during the ‘secondary’ process of learning (e.g., knowing orthographic constraints and context sensitive rules assists the establishment of orthographic representations). These alternatives cannot be distinguished in the present study and require further investigation.

Importantly, we found that visual-verbal paired-associate learning ability remained a significant predictor of orthographic learning even after orthographic knowledge and phonological decoding ability had been accounted for. This is likely due to the difference between a child’s historic, or crystalised, ability in reading and the ability to learn online. More specifically, although orthographic knowledge may be reflecting a child’s pre-existing word knowledge, and be indexing to some extent his or her previous orthographic learning ability, this crystalised knowledge may be reflecting a combination of factors. For example, a child’s orthographic knowledge could be influenced by how he or she has been taught to read, how much support was provided from oral vocabulary knowledge, or the number of exposures he or she has had over a long period of time. On the other hand, the paired-associate learning task is a pure index of a child’s dynamic ability to learn pairings between visual and verbal items. Consequently, paired-associate learning ability was able to account for unique variance in orthographic learning in addition to crystalised orthographic knowledge.

Finally, it is important to consider how visual-verbal paired-associate learning interacts with the two known contributors to orthographic learning, phonological decoding and orthographic knowledge. The self-teaching hypothesis suggests that orthographic learning is a two-step process: phonological decoding first and orthographic knowledge second. One way to consider the role of paired-associate learning ability in this process is that this ability is one of the factors that underpins the second component, orthographic knowledge. However, as this second component has yet to be clearly defined (Share, 2008; Wang et al., 2014), it is difficult to be more specific about how this process might operate. Another possibility is that paired-associate learning is a third component that has not been specified in the self-teaching hypothesis. In this case, paired-associate learning ability contributes to forming a connection between the phonology (a product of step one, phonological decoding) and the orthography (a product of step two, orthographic knowledge).

Building on the self-teaching hypothesis, we propose the following process of orthographic learning. Phonological decoding provides the first step of producing the correct phonology of the word, and at the same time draws a reader's attention to the orders and details of the letters of the word (e.g., Share, 1995). Orthographic knowledge assists the learning process by helping the reader to analyse the orthographic input, to combine letters into larger units (Ehri, 2014), and to consolidate the orthographic representation. Paired-associate learning ability helps to establish the connection between the phonology and orthographic representation of the word, and may support further consolidation of precise orthographic knowledge through co-activation of the orthography from the phonology. These three factors together contribute to successful acquisition of orthographic representations.

It should be noted that this proposed mechanism of orthographic learning is largely based on correlational relationships between the three factors under investigation and orthographic learning ability, and is just one of a range of mechanisms that could be proposed. Further research is required to test the hypothesis that there are direct casual relationships between them, especially for paired-associate learning ability and orthographic knowledge. In addition, the orthographic learning results from this study were based only on a spelling measure administered immediately after learning. Therefore, it remains unclear how these important factors are related to the consolidation of orthographic representations over time. It would be valuable to use more sensitive measures of orthographic learning such as eye-tracking or masked priming, and over a longer period of time, to further elucidate their associations with phonological decoding, orthographic knowledge, and different types of paired-associate learning. Another limitation of the study is that, as with many experimental learning studies, sample size was limited. Further research replicating the results of the regression analyses with a larger group and more items would be valuable.

In summary, this study was the first to directly examine the role of paired-associate learning in the ability to learn novel orthographic representations. We found that visual-verbal paired-associate learning ability predicted orthographic learning over and above phonological decoding skill and orthographic knowledge. The findings of the study contribute to a better understanding of the relationship between paired-associate learning and reading development. More importantly, we propose that paired-associate learning ability may play a role in the process of orthographic learning, by supporting the formation of connections between the orthography and the phonology of newly learned words.

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