LSHSS

Research Article

Orthographic Learning in Children Who Are Deaf or Hard of Hearing

Malin Wass,[a] Teresa Y. C. Ching,[b,c] Linda Cupples,[d] Hua-Chen Wang,[e,f] Björn Lyxell,[g] Louise Martin,[b,c] Laura Button,[b,c] Miriam Gunnourie,[b,c] Isabelle Boisvert,[c,h] Catherine McMahon,[d,f] and Anne Castles[e,f]

Purpose: The purpose of the current study was to investigate the relationship between orthographic learning and language, reading, and cognitive skills in 9-year-old children who are deaf or hard of hearing (DHH) and to compare their performance to age-matched typically hearing (TH) controls.

Method: Eighteen children diagnosed with moderate-to-profound hearing loss who use hearing aids and/or cochlear implants participated. Their performance was compared with 35 age-matched controls with typical hearing. Orthographic learning was evaluated using a spelling task and a recognition task. The children were assessed on measures of reading ability, language, working memory, and paired-associate learning.

Results: On average, the DHH group performed more poorly than the TH controls on the spelling measure of orthographic learning, but not on the recognition measure. For both groups of children, there were significant correlations between orthographic learning and phonological decoding and between visual–verbal paired-associate learning and orthographic learning.

Conclusions: Although the children who are DHH had lower scores in the spelling test of orthographic learning than their TH peers, measures of their reading ability revealed that they acquired orthographic representations successfully. The results are consistent with the self-teaching hypothesis in suggesting that phonological decoding is important for orthographic learning.

Early in the process of learning to read, children need to learn that letters represent speech sounds, which can be blended to form words and sentences (e.g., Ehri, 2005, 2014). Children can then use this basic knowledge to sound out words, a reading process referred to as *phonological (sublexical) decoding* (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). This reading process is highly dependent on phonological skills, such as the ability to discriminate, store, and process speech sounds (e.g., Anthony & Francis, 2005; Ehri, 2005; Goswami et al., 2010; Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012). Phonological decoding is the most common reading process for children early in reading development, but it is an effortful reading strategy (Castles et al., 2009). Most experienced readers use phonological decoding when reading unfamiliar words (Rau, Moeller, & Landerl, 2014), but they use a more efficient strategy, which we refer to here as *orthographic word recognition*, for reading familiar words. The latter involves rapid recognition of whole words, and it is achieved through comparing presented written words to long-term memory representations of their spellings (Castles et al., 2009; Castles, Davis, Cavalot, & Forster, 2007). Orthographic word recognition is automatized and efficient for reading familiar words but is not possible to use for reading unfamiliar words (Ehri, 2005). In order to be a quick and fluent reader, the child needs to build up a large internal lexicon of orthographic representations in long-term memory. The process of building up new orthographic representations is referred to as *orthographic learning* (Nation & Castles, 2017), and it is essential in order to

[a]Department of Business Administration, Technology and Social Sciences, Luleå University of Technology, Sweden
[b]National Acoustic Laboratories, Sydney, NSW, Australia
[c]The HEARing Cooperative Research Centre, Sydney, NSW, Australia
[d]Department of Linguistics, Macquarie University, Sydney, NSW, Australia
[e]Department of Cognitive Science, Macquarie University, Sydney, NSW, Australia
[f]ARC Centre of Excellence in Cognition and its Disorders, Macquarie University, Sydney, NSW, Australia
[g]Department of Behavioural Sciences and Learning, Linköping University, Sweden
[h]Centre for Implementation of Hearing Research, Macquarie University, Sydney, NSW, Australia
Correspondence to Malin Wass: malin.wass@ltu.se

Editor-in-Chief: Shelley Gray
Editor: Patricia Brooks
Received December 10, 2017
Revision received March 7, 2018
Accepted July 9, 2018
https://doi.org/10.1044/2018_LSHSS-17-0146

Disclosure: *The authors have declared that no competing interests existed at the time of publication.*

become a skilled reader. This study investigated orthographic learning and reading ability in children who are deaf or hard of hearing (DHH) and the cognitive and linguistic factors that are associated with these skills.

Theories and Predictors of Orthographic Learning

The most prominent theories of orthographic learning are the self-teaching model (Share, 1999, 2004) and the theory of sight word learning (Ehri, 1992). According to the self-teaching model, children acquire detailed orthographic representations of words as they read, primarily by means of phonological decoding. They memorize the spellings of words through the process of translating print into sound, and only a few exposures can be sufficient for skilled readers to acquire correct representations (Nation, Angell, & Castles, 2007; Share, 2004). Phonological decoding is thus considered essential for orthographic learning, and this is supported by studies that have demonstrated a strong association between the two variables (e.g., Bowey & Muller, 2005; Kyte & Johnson, 2006; Share, 1999, 2004). Furthermore, experimental studies have revealed a substantial decrease in orthographic learning when phonological decoding is prevented by instructing children to produce another irrelevant nonsense word at the time when they are presented with written words to be learned (De Jong, Bitter, van Setten, & Marinus, 2009; Kyte & Johnson, 2006; Share, 1999).

Within the theory of sight word learning (Ehri, 1992, 2014), the concept of orthographic mapping is used to refer to the process of acquiring new orthographic representations, that is, orthographic learning. On this view, children form connections between written units (e.g., graphemes or larger spelling units) and spoken units (e.g., phonemes, syllables or morphemes) as they read specific words (Ehri, 1998, 2014). These connected orthographic–phonological representations are then stored in long-term memory together with their semantic representations, thereby enabling readers to recognize words by sight (Ehri, 2005, 2014). After the stage of blending the subunits in unfamiliar, phonologically decoded words, orthographic mapping also involves searching the mental lexicon for a matching spoken word that makes sense in the semantic context (Ehri, 2005, 2014). In irregular orthographies, where phonological decoding may result in incorrect pronunciations, the reader needs to repeatedly search the mental lexicon for a matching spoken word. An extensive vocabulary of spoken words thus increases the likelihood of correctly matching a decoded word to its corresponding spoken form in long-term memory (Ehri, 2014; Share, 1995). Recent findings from Wegener et al. (2018) further suggests that, for children in Grade 4 who have acquired a certain level of reading skill, the process of building up an orthographic representation of a word starts with spoken vocabulary; that is, when the word is heard for the first time, before it is seen in print, children start to build up an anticipated representation based on the phonological form of the word. For words with regular spellings, the anticipated representation facilitates reading when the word is first seen in print (Wegener et al., 2018).

Based on Ehri's orthographic mapping concept, there are two key cognitive predictors of orthographic learning, besides phonological decoding. They are proposed to be existing orthographic knowledge (e.g., Cunningham, 2006; Cunningham, Perry, Stanovich, & Share, 2002) and paired-associate learning (PAL; Wang, Wass, & Castles, 2017). Orthographic knowledge refers to the knowledge of spelling patterns in the language in question (Ehri, 2005, 2014). It has typically been measured in tasks that require correct spellings of words to be discriminated from pseudohomophones (e.g., *lake–laik*) or in tasks involving decisions about which of a few spelling patterns look more correct (e.g., *ract* or *rackt*). Orthographic knowledge may be used to facilitate the process of memorizing the spelling of words (Ehri, 2014); that is, spelling patterns that are already familiar are easier to remember. In the process of orthographic mapping, the ability to recognize identical spelling patterns or orthographic knowledge of a subunit of a word in the mental lexicon may guide the pronunciation of the word to be learned (Ehri, 2014). PAL refers to the process of learning arbitrary associations between stimulus items and response items in memory (Litt, De Jong, Van Bergen, & Nation, 2013). According to the multicomponent model of working memory (e.g., Baddeley, 2012), PAL tasks are considered to reflect the capacity to bind different pieces of information in the episodic buffer of working memory before transfer into long-term memory (Allen, Hitch, & Baddeley, 2009; Burgess & Hitch, 2005). In general, working memory is involved in all tasks that require PAL, in particular, for learning spoken vocabulary at an early age and when learning a second language (Baddeley, 2012; Gathercole, 2006). PAL has been measured in tasks where a child is required to link two pieces of information (Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Litt & Nation, 2014). The information may be presented in the same or different modalities, for example, two pieces of visual information (e.g., shapes), two pieces of verbal information (e.g., words or nonwords), or cross-modal association with one piece of verbal and one piece of visual information (e.g., shape and nonword; see Appendix). However, only measures of visual–verbal and verbal–verbal PAL have been found to associate with reading (e.g., Litt & Nation, 2014) and orthographic learning (Wang et al., 2017). PAL may be involved in the acquisition of an orthographic lexicon when, at a later point in reading development, children learn to associate whole written words with their pronunciations without having to decode phonologically (Hulme et al., 2007; Lervåg, Bråten, & Hulme, 2009; Litt & Nation, 2014; Messbauer & de Jong, 2003).

Predictors of Reading and Orthographic Learning in Children Who Are DHH

Reading skill has been studied to some extent in children who are DHH, although that research has typically focused on general measures of decoding and reading comprehension, rather than on orthographic learning in particular (cf. Geers & Hayes, 2011; Moeller, Tomblin, Yoshinaga-Itano, McDonald Connor, & Jerger, 2007).

Some of the skills that predict orthographic learning in typically hearing (TH) children have, however, been studied in children who are DHH and are reviewed below.

First of all, it should be acknowledged that, for children who are DHH, perception of the acoustic–phonetic details of language is poorer compared with TH peers (Brown & Bacon, 2010; Pisoni et al., 2008; Tomblin et al., 2015). This deficit, in turn, leads to poorer phonological skills (Lyxell et al., 2008; Pisoni et al., 2008), and according to a large number of research studies on TH children, weaknesses in phonological skills should be expected to result in poorer phonological decoding skills (e.g., Goswami et al., 2010; Hulme et al., 2012). A number of studies have indeed demonstrated poorer reading skills in children who are DHH (e.g., Geers, 2003; Geers & Hayes, 2011; Harris & Terlektsi, 2010; Johnson & Goswami, 2010; Kyle & Harris, 2006; Moeller et al., 2007). As none of these studies specifically addressed different decoding strategies and often used composite measures of phonological decoding and orthographic word recognition, those difficulties may reflect problems with phonological reading processes, orthographic word recognition, or both. However, Johnson and Goswami (2010) found some evidence for a selective reading difficulty in a sample of 53 DHH children fitted with a cochlear implant (CI) and/or hearing aid (HA). The children performed below the level of TH peers on measures of single word oral reading assessed in the British Ability Scales–Second Edition (Elliott, Smith, & McCulloch, 1996) yet had age-appropriate performance on visual word recognition measured in a word chains test where they were asked to split word chains into separate words, for example, *catcoffeehigh* should be *cat*, *coffee*, and *high* (Miller-Guron, 1999). Also, results from Nakeva von Mentzer et al. (2014) for 5- to 7-year-old children who are DHH and fitted with traditional hearing aids and/or CIs indicate relatively poorer performance on measures of nonword decoding as compared with word reading. Based on the self-teaching hypothesis of orthographic learning (Share, 1995, 1999), these relatively poor phonological decoding skills in children who are DHH would, in turn, suggest that they also have poorer orthographic learning ability.

Regarding spoken vocabulary, which is considered important for word decoding in TH children, several studies have found delays in vocabulary development for children with various degrees of hearing loss (see overview by Moeller et al., 2007). The results vary between studies, however, depending partly on the degree of hearing loss. Delays in the development of receptive vocabulary have recently been confirmed in 6- to 9-year-old children with mild–moderate hearing loss who use hearing aids (Stiles, McGregor, & Bentler, 2012). Regarding children with profound hearing loss who use cochlear implants, Geers, Moog, Biedenstein, Brenner, and Hayes (2009) found that only 50%–58% of 153 children fitted with CI before 24 months of age demonstrated receptive and expressive vocabulary skills within the expected range for TH children at ages 5–6 years. Similarly, Fagan and Pisoni (2010) demonstrated that children with CI between 6 and 14 years of age performed significantly below chronological age–matched TH children on receptive vocabulary, whereas they performed on par with younger TH children who have the same amount of hearing experience. This documented weakness in spoken vocabulary would be expected to complicate the process of orthographic learning by means of self-teaching in children who are DHH, because with a less extensive spoken vocabulary, they will less frequently be able to match unfamiliar written words to their spoken counterparts (cf. Ehri, 2014; Share, 1995; Wegener et al., 2018).

Orthographic knowledge is another predictor of orthographic learning that has been investigated in previous research with DHH children who have varying degrees of hearing loss (cf. overview by Leybaert, 2007). The results indicate that DHH children have a relatively high level of orthographic knowledge. For example, findings from Transler and Reitsma (2005) indicate that DHH Dutch children performed at a similar level as children with typical hearing on a lexical decision task. Furthermore, a study by Kyle and Harris (2006) found no significant group differences in spelling ability between 29 seven- and eight-year-old DHH children in comparison with reading-matched TH peers. These results suggest that DHH children may have relatively higher levels of orthographic knowledge compared with their phonological skills and reading ability. Based on the documented positive relationship between orthographic knowledge and orthographic learning (cf. Cunningham, 2006; Ehri, 2005), these strengths in orthographic knowledge for children who are DHH would, in turn, be expected to facilitate their orthographic learning and, hence, to counteract, to some degree, the negative impact of their weaknesses in phonological decoding. PAL is another factor that is expected to affect orthographic learning in children who are DHH (cf. Wang et al., 2017). To our knowledge, PAL has not previously been investigated in this group of children, but it was investigated in the current study.

To sum up, the four skills reviewed above—phonological decoding, spoken vocabulary, orthographic knowledge, and PAL—have all been proposed to have central roles in orthographic learning for TH children. Children who are DHH have been reported to perform more poorly than TH peers on phonological decoding and measures of spoken vocabulary. They would thus be expected to have more difficulties in tasks of orthographic learning than typically developing readers.

No research to date has directly examined whether orthographic learning is compromised in children who are DHH, but it is important to do so both to understand how children who are DHH learn to read and to further understand the role of phonological processing and phonological decoding in theories of orthographic learning. A central question is whether the nature of the orthographic learning process in children who are DHH, and the cognitive skills that they draw on, differ from those used by TH children. Because of the auditory and phonological weaknesses in children who are DHH, it might be expected that they would rely more heavily on other skills such as PAL, receptive vocabulary, and orthographic knowledge in order to establish new orthographic representations.

The Current Study

The aim of the current study was twofold. First, we wanted to examine orthographic learning in children who are DHH, using CIs and/or traditional hearing aids, and compare it with that of TH children. In addition, we wanted to compare the two groups on phonological decoding measures in order to examine whether these skills are impaired in children who are DHH and whether they are associated with orthographic learning performance. The second aim was to examine the cognitive and linguistic correlates of orthographic learning in children who are DHH and to assess whether they differed from those for TH children.

No previous research has, to our knowledge, specifically investigated orthographic learning in children who are DHH. Therefore, we adopted an exploratory research strategy including a broad range of cognitive and linguistic measures, which have all been suggested to affect orthographic learning and/or reading skill in other populations. Based on the self-teaching model, we hypothesized that the children who are DHH would have more difficulties overall in orthographic learning than TH children. However, based on the findings from Johnson and Goswami (2010) and Nakeva von Mentzer et al. (2014) that children who are DHH have relatively higher performance on word recognition than on phonological decoding, we hypothesized that they may perform relatively better on orthographic learning than would be predicted based on their phonological skills. We also expected that skills other than phonological decoding, for example, PAL, working memory, receptive vocabulary and orthographic knowledge, would be related to their orthographic learning ability.

This research was approved by the Research Ethics Review Committee of the Sydney Local Health District and the Human Research Ethics Committees at Macquarie University and Australian Hearing.

Method

Participants

A total of 53 children, ages 9;0 (years;months) to 9;11, were recruited for the study. Thirty-five children (18 girls and 17 boys) had typical hearing, and 18 children (11 girls and 7 boys) had been diagnosed with a hearing loss ranging from moderate to profound prior to receiving hearing aids or cochlear implants. All children had normal or corrected vision and no known learning disabilities. Nonverbal IQ above 85 was used as a selection criterion for participation. The reading levels in the group of children with typical hearing were in the normal range based on the Coltheart and Leahy (1996) norms for 9-year-old children (i.e., z scores above −1.3 on measures of nonword decoding and irregular word decoding). At the time of testing, their average chronological age was 9 years 5 months (SD = 3.5 months, range: 8;10–9;11). Twenty-nine of the TH children were recruited from three mainstream primary schools in the Central Coast region of Australia. Those children were tested in quiet rooms at their schools. Six children in the TH control group were recruited from advertisements and were tested at Macquarie University.

The 18 children who are DHH were participants of the Longitudinal Outcomes of Children with Hearing Impairment study (Ching, Leigh, & Dillon, 2013) and completed the assessments for this study as part of their 9-year battery. The degree of hearing loss was specified in terms of four-frequency average hearing level (average of hearing thresholds at 0.5, 1, 2, and 4 kHz) in the better ear. They were diagnosed with hearing loss at a mean age of 7.0 months (SD = 8.4 months) but had no known additional disabilities. The average age of the DHH group at the time of testing was 9 years 4 months (SD = 4.1 months, range: 9;0–9;11). Degree of hearing loss and hearing aid use for the DHH group is displayed in Table 1. The two groups were matched for socioeconomic background, and the children were all educated in English and fluent speakers of English.

Tests and Procedures

All children were tested individually and completed the test measures in two 1-hr sessions. To avoid fatigue, the two test sessions were completed on separate days. A range of measures to assess reading ability, orthographic learning, PAL, working memory, and language skills was administered to all participants (see Table 2 for a summary). All of the tests included practice items where the experimenter made sure the child understood the task. For those tests that involved an auditory component, the experimenter ensured that children could perceive the test items by asking them to repeat the word and/or nonword stimuli.

Reading Measures

Reading accuracy was tested using the Coltheart and Leahy (1996) reading assessment in which children were asked to read aloud 30 irregular words, for example, *iron,* and 30 nonwords, for example, *gurve,* presented on a 14-in. laptop screen (screen resolution: 1366 × 768). Orthographic reading processes were assessed using irregular words and phonological reading processes using nonwords. Every child attempted to read all 60 words, with no discontinuation rule applied. Each response was recorded by the experimenter, and accuracy was scored subsequently as 1 or 0.

Reading fluency for words and nonwords was assessed using the Test of Word Reading Efficiency (TOWRE with Australian norms; Marinus, Kohnen, & McArthur, 2013). This test comprises two subtests: one using words of varying

Table 1. Use of hearing technologies and degree of hearing loss in the deaf or hard of hearing group.

	Traditional HA		CU=I	
Hearing loss	Bilateral	HA + CI	Unilateral	Bilateral
Moderate	7		1	
Severe–profound	1	3		6

Note. HA = hearing aid; CI = cochlear implant.

Table 2. Tests administered.

Ability	Test	Quantification
Measures of language and cognitive skills		
Visual working memory	Matrix Pattern Test (Wass et al., 2008)	Number of cells in the most difficult pattern correctly reproduced (maximum score = 8)
Phonological short-term memory	CTOPP Memory for Digits subtest (Wagner et al., 1999)	Number of correctly repeated series of digits (maximum score = 21)
Visual–visual PAL	Test adapted from Hulme et al. (2007)	Number of correct answers (maximum score = 20)
Visual–verbal PAL	Test adapted from Hulme et al. (2007)	Number of correct answers (maximum score = 20)
Verbal–verbal PAL	Test adapted from Hulme et al. (2007)	Number of correct answers (maximum score = 20)
Receptive vocabulary	PPVT-4 (Dunn & Dunn, 2007)	Number of correctly identified pictures (maximum score = 228)
Rapid naming	CTOPP Rapid Color Naming subtest (Wagner et al., 1999)	Number of seconds to name all colors
Phonological skills	CTOPP Segmenting Nonwords	Number of correctly segmented nonwords (maximum score = 20)
Phonological reading processes		
Nonword decoding accuracy	C&L nonwords (Coltheart & Leahy, 1996)	Number of correctly read nonwords (maximum score = 30)
Nonword decoding fluency	TOWRE nonwords Form A + B (Marinus et al., 2013)	Number of correctly read nonwords (maximum score = 126)
Orthographic reading processes		
Word reading accuracy	C&L irregular words (Coltheart & Leahy, 1996)	Number of correctly read irregular words (maximum score = 30)
Word reading fluency	TOWRE words Form A + B (Marinus et al., 2013)	Number of correctly read words (maximum score = 208)
Existing orthographic knowledge	Orthographic choices (TOC; Kohnen et al., 2012)	Number of correctly identified spellings (maximum score = 30)
Orthographic learning		
Orthographic learning	Test adapted from Byrne et al. (2008) and Wang et al. (2011)	Number of correctly spelled nonwords (maximum score = 16)
Orthographic learning recognition measure	Test adapted from Wang et al. (2011)	Number of correctly recognized nonwords (maximum score = 16)

Note. CTOPP = Comprehensive Test of Phonological Processing; PAL = paired-associate learning; PPVT-4 = Peabody Picture Vocabulary Test–Fourth Edition; TOWRE = Test of Word Reading Efficiency; C&L = Coltheart and Leahy (1996) reading assessment; TOC = Test of Orthographic Choice.

length and the other using nonwords, also of varying length, for example, *ib* and *lunaf*. In each subtest, the child was required to read correctly as many items as possible in 45 s. This procedure was repeated twice using the A and B versions of the test. The children received a point for every item read correctly.

Existing orthographic knowledge was measured using the Test of Orthographic Choice (TOC; Kohnen, Anandakumar, McArthur, & Castles, 2012). This test contains target words presented together with pseudohomophone distractors. The 30 target words were selected from the Children's Printed Word Database (Masterson, Stuart, Dixon, Lovejoy, & Lovejoy, 2003), which ranged in frequency from three to 625 instances per million words. Pseudohomophone distractors were created using alternative, homophonic spellings for vowels (e.g., FLAME changed to FLAIM) or consonants (e.g., CURL changed to KURL). Each item was paired with its alternative homophonic spelling, and the child was asked to circle the correct spelling of the word.

Orthographic Learning

The ability to acquire new lexical orthographic representations was assessed using an orthographic learning task adapted from Byrne et al. (2008). There were, in total, 16 target items for children to learn. Eight of the target items were presented in short stories (context condition), and eight were presented in tables without a semantic context (no-context condition). This manipulation was included in response to previous findings suggesting that individual differences in orthographic learning ability may be modulated by the provision of contextual information (Landi, Perfetti, Bolger, Dunlap, & Foorman, 2006; Wang, Castles, Nickels, & Nation, 2011). The context condition and the no-context condition subtests were conducted on separate days, and the order of test conditions was counterbalanced within each group of children. All of the target items were four- to six-letter nonwords taken from Byrne et al. (2008) and Wang et al. (2011). All of the nonwords had regular letter–sound mappings but inconsistent spellings (e.g., /cleep/ can be spelled as *clepe, cleap, kleep*). Hence, word-specific orthographic knowledge was required to learn to spell the target words correctly.

In the context condition, every nonword item appeared four times in a short story. The stories averaged 27 words in length and were presented on an A4 size paper in a 22-point font. Each story started with the sentence "The new word is ____," followed by a narrative containing three more instances of the novel word (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 child was instructed that he or she would read the stories together with the experimenter and that he or she would take on reading every time the experimenter stopped. The children read, on average, nine words from each story, including all four instances of the new word. This adaptation of the original test setup (cf. Wang et al., 2011) ensured that the task of reading the stories would not be too taxing or time consuming for any child.

In the no-context condition, the target items were presented four times in tables together with the same number of real words as the story in the semantic context condition. The nontarget words presented in the no-context condition were matched with the nontarget words in the context condition for frequency, length, and word class in the Children's Printed Word Database (Masterson et al., 2003).

In both the context and no-context conditions, orthographic learning was assessed in two tasks: spelling and orthographic choice (previously described in Wang et al., 2011). These tests were conducted directly after exposure to every fourth test item; that is, the child was exposed to target items 1–4, and directly afterwards, he or she was assessed on the measures of spelling and orthographic choice for those items. This procedure was then repeated for the second set of test items (5–8). For the spelling task, children were asked to write each of the new words to dictation. They were encouraged to write the words exactly as they appeared in the stories. The first sentence from each story served as a prompt (e.g., "There is a kind of boat called a laif. Write laif."). Accuracy for every target word was scored as 1 or 0. For the orthographic choice task, each target item was presented together with its pseudohomophones and two visual distractors (e.g., laif, lafe, laip, lape). The visual distractors were also pseudohomophones and contained the same middle vowel as the target. For every target word, the four options were presented horizontally on an A4 size paper. The children were instructed that only one of the four options had the correct spelling.

PAL

Three types of PAL were assessed in this experiment: visual–visual, visual–verbal, and verbal–verbal (adapted from Hulme et al., 2007). The visual–visual and the verbal–verbal conditions were conducted during the same session, whereas the visual–verbal condition was conducted in the other test session.

Visual–visual PAL. This condition of the task was assessed only as a comparison to verbal–verbal and visual–verbal PAL. Based on findings from previous research (e.g., Hulme et al., 2007; Litt et al., 2013; Wang et al., 2017), we did not expect to find any significant association between visual–visual PAL and the reading measures, but similar to previous research, it was used to ensure that the children did not have a general problem with PAL across different modalities.

In this task, children were asked to learn which shapes went together. Two sets of different 8-point shapes were taken from Vanderplas and Garvin (1959), printed in black, and put onto cards. Each set contained four different shapes and had a different background color. First, one set of four shapes was laid out in a row in front of the child. The experimenter then placed each shape from the second set next to its pair from the first set. When the two shapes were placed adjacent to each other, the experimenter said, "This shape goes with this shape." The two shapes remained adjacent for 5 s, before 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 shapes to be scored as correct. The experimenter recorded the child's responses and provided feedback about which answer was correct. This procedure was repeated five times, making a total of 20 learning trials, which were all used as responses.

Visual–verbal PAL. In this task, the child was asked to learn which shape went with which spoken nonsense word. Another set of shapes was made in the same way as those used in the visual–visual PAL condition. The nonsense words, which were selected from the Diagnostic Spelling Test (Kohnen, Nickels, & Castles, 2009), each contained three phonemes in a consonant–vowel–consonant format, although in some cases, individual phonemes would be represented using digraphs if spelled according to English sound–letter rules (e.g., l-ur-th). During the task, the experimenter first asked the child to repeat the four nonwords used (leet, zorm, heg, nam) in order to make sure that he or she was able to perceive and pronounce them. The experimenter held a set of four cards with shapes. She showed the child one card at a time and said the associations twice. For example, "This shape goes with huk, [2-s interval], this shape goes with huk." After all four pairs were introduced, the experimenter presented one card at a time and asked the child, "Which nonsense word goes with this shape?" The experimenter recorded the child's responses, and feedback was given on each trial, in the same format as in the initial presentation, for example, "Do you remember? This shape goes with huk." This procedure was also repeated five times, making a total of 20 learning trials/responses.

Verbal–verbal PAL. In this task, the child was asked to learn which spoken nonsense words went together 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, for example, "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?" The responses were recorded by the experimenter, and feedback of the same kind as in the initial presentation was provided, for example, "Do you remember? 'darp goes with tem.'" The procedure was repeated five times, making a total of 20 learning trials/responses.

Working Memory

Phonological short-term memory. The Comprehensive Test of Phonological Processing (CTOPP) Memory for

Digits subtest (Wagner, Torgesen, & Rashotte, 1999) was used to assess phonological short-term memory. In this test, the child listened to a voice recording of a female speaker, presenting series of digits of increasing length. The child was asked to repeat the series of digits in the exact order of presentation and received one credit for every digit recalled in the correct order.

Visual working memory. In the current study, visual–spatial short-term memory was assessed in a matrix pattern span task (Wass et al., 2008). The procedure of the matrix pattern test is as follows: Patterns of filled cells are displayed in a 5 × 5 matrix on a computer screen. After presentation of any given pattern, the filled cells disappear, and the child is then asked to click on the previously filled cells in an empty matrix. The level of difficulty increased from one to eight filled cells. The task was discontinued when children made mistakes on at least two out of three patterns on two consecutive complexity levels. The children received span scores for the highest level of difficulty at which they correctly reproduced two out of three test patterns. For example, if a child correctly reproduced two patterns with four filled cells, he or she received a visual span score of 4.

Language Skills

Receptive vocabulary. The Peabody Picture Vocabulary Test–Fourth Edition (Dunn & Dunn, 2007) was used to measure receptive vocabulary. Participants were shown four pictures on each trial and asked to point to the picture that matched the word spoken by the experimenter. Testing began and ended according to test-specific basal and ceiling rules; testing ended after eight errors were made in a set of 12 items.

Rapid naming. Lexical access/rapid serial naming was assessed using the Rapid Color Naming subtest of the CTOPP battery (Wagner et al., 1999). In this test, the child was presented with a page containing 36 squares in different colors. The task was to say the color name for all of the squares in the form, row by row, as quickly as possible. The raw score equaled the number of seconds that it took to name all colors.

Phonological skills. Phonological skills were assessed in CTOPP Segmenting Nonwords subtest (Wagner et al., 1999). The children were presented with a voice recording of a female speaker, presenting nonwords such as *pask* that the children were asked to repeat and then segment into constituent phonemes *p-a-s-k*. The children received one credit for every correctly segmented nonword.

Hearing Screening for TH Controls

Otoacoustic emissions were used to screen for hearing ability in the control group. Children who did not pass the otoacoustic emission screening were excluded.

Statistical Analysis

Statistical analyses were performed on raw scores with one exception. In the correlation analyses (see Tables 4–7), a composite measure of nonword decoding was used in order to limit the number of correlations computed. The composite measure was computed by adding z scores from the two nonword decoding tests, TOWRE nonwords and Coltheart and Leahy nonwords. Group comparisons were conducted using Mann–Whitney U tests. We initially manipulated the provision of contextual information in the orthographic learning task. However, context and no-context conditions were highly correlated with each other ($r = .76$), and due to the fact that the two conditions showed very similar results in the two participant groups, we have combined scores of the two conditions in all analyses to increase statistical power.

Due to the exploratory nature of this work, results that are significant at $\alpha < .05$ are presented in the tables and discussed below. This approach was adopted to reduce the likelihood of ignoring potentially significant relationships (Type 2 error; cf. Bender & Lange, 2001; Perneger, 1998). However, because it carries with it the risk of reporting that results are significant when they are not (Type 1 error), those that remained significant after Bonferroni correction for multiple comparisons are also indicated in the tables for comparison.

In order to explore the relationship between orthographic learning and cognitive variables, nonparametric Spearman rank order correlations were computed for each participant group separately.

Results

Descriptive Statistics and Group Comparisons

Descriptive statistics and group comparisons for all cognitive/linguistic tests and reading measures are displayed in Table 3.

Measures of Reading Skill and Orthographic Learning

With respect to reading measures (see Table 3), the DHH group had significantly lower mean scores than the controls, not only on the phonological reading measures but also on the orthographic reading measures, with effect sizes in the moderate range, $r = .3–.4$. There was no significant difference between the DHH and TH groups on the TOC, which is a measure of orthographic reading that reflects existing orthographic knowledge.

The results for orthographic learning were mixed. Whereas children with typical hearing performed significantly better than their DHH peers on the spelling measure of orthographic learning (effect size $r = -.40$), no significant group difference was found on the recognition measure (see Table 3).

Correlation Analyses

Spearman rank order correlations are presented for each group separately in Tables 4–7. Correlations between reading measures for children in the DHH group are presented in Table 4 and for children in the TH control group in Table 5. Correlations between reading measures and cognitive skills are presented in Table 6 for DHH children and in Table 7 for TH controls. It should be noted that, for

Table 3. Descriptive statistics and group comparisons (Mann–Whitney *U* test) for cognitive/linguistic tests and reading measures.

Cognitive/linguistic measure (max score)	TH		DHH		Mann–Whitney *U*	Effect size, *r*	*p*[a]
	n	*M* (*SD*; range)	*n*	*M* (*SD*; range)			
Visual WM (8)	35	4.77 (1.40; 2–8)	16	3.94 (1.12; 2–6)	180.5	−.29	.037
Visual–visual PAL (20)	35	14.69 (3.76; 5–20)	15	13.53 (3.40; 10–20)	204.0	−.18	.213 n.s.
Visual–verbal PAL (20)	35	13.94 (4.14; 0–20)	14	10.21 (4.87; 4–20)	125.5	−.38	.008
Verbal–verbal PAL (20)	35	9.94 (5.63; 0–19)	15	6.6 (4.17; 1–15)	169.5	−.28	.048
PPVT-4 (228)	35	158.83 (17.49; 121–192)	18	133.17 (23.58; 84–165)	127.5	−.48	.000[b]
RAN colors	35	54.83 (10.19; 36–81)	15	78.47 (23.5; 48–137)	82.5	−.54	.000[b]
Digit span (21)	35	14.06 (2.67; 10–20)	16	12.31 (3.63; 7–19)	196.0	−.24	.087 n.s.
Segmenting nonwords (20)	35	13.23 (4.82; 0–20)	16	4.19 (3.08; 0–10)	42.0	−.68	.000[b]
Phonological reading processes							
C&L nonwords (30)	35	24.38 (4.60;16–30)	16	17.38 (9.94; 0–30)	164.5	−.33	.018
TOWRE nonwords (63)	35	36.04 (11.08; 14.5–58.5)	16	25.78 (17.09; 1.5–51)	182.5	−.28	.048
Orthographic reading processes							
C&L irregular words (30)	35	22.66 (2.95; 18–27)	16	17.94 (5.14; 7–24)	124.5	−.44	.002[b]
TOWRE words (104)	35	68.59 (9.53; 44–86)	16	60.19 (14.02; 28–83.5)	171.0	−.31	.027
Orthographic choices (TOC; 30)	35	24.91 (5.31; 0–30)	14	23.36 (4.99; 12–29)	186.0	−.19	.190 n.s.
Orthographic learning							
OL spelling measure (16)	35	12.63 (2.83; 6–16)	16	8.75 (4.58; 2–16)	141.0	−.40	.005
OL recognition measure (16)	35	14.40 (1.72; 9–16)	16	12.75 (3.19; 5–16)	194.5	−.25	.076 n.s.

Note. TH = typically hearing; DHH = deaf or hard of hearing; visual WM = visual working memory (matrix patterns test); PAL = paired-associate learning; PPVT-4 = Peabody Picture Vocabulary Test–Fourth Edition; RAN colors = CTOPP Rapid Naming (colors); Segmenting Nonwords = CTOPP Segmenting Nonwords; Digit span = CTOPP Digit span; C&L = Coltheart and Leahy (1996) reading assessment; TOWRE = Test of Word Reading Efficiency; TOC = Test of Orthographic Choice; OL = orthographic learning; n.s. = not statistically significant..

[a]*p* value from Mann–Whitney *U* test comparing DHH with normal hearing groups. [b]*p* value significant also after Bonferroni correction for multiple comparisons (α < .003).

the children who are DHH, no significant correlations were found between orthographic learning and any of the demographic variables, namely, speech perception, age of diagnosis, or hearing level.

Relationship Between Reading Measures and Orthographic Learning

For the DHH group, the spelling measure of orthographic learning was strongly correlated with nonword decoding and orthographic knowledge, *r*s = .8. The recognition measure of orthographic learning was significantly correlated only with the nonword decoding measure, *r* = .7.

In the TH group, orthographic learning (spelling) was significantly correlated with all of the reading measures, although only the correlation with nonword decoding was in the higher range (*r* > .5). The correlation between the recognition measure of orthographic learning and orthographic reading (Coltheart and Leahy irregular words) was in the moderate range, *r* = .4.

Relationship Between Cognitive Skills and Orthographic Learning

Regarding the cognitive measures, both the spelling and recognition measures of orthographic learning were significantly correlated with visual–verbal PAL in the DHH group, with Spearman *r*s slightly above .5. The spelling measure of orthographic learning was further correlated with verbal–verbal PAL (*r* > .5).

Table 4. Spearman correlations between measures of reading and orthographic learning for the deaf or hard of hearing group.

Measure	1	2	3	4	5	6
1. Nonword decoding composite[a]	—					
2. C&L irregular words	.685**	—				
3. TOWRE words	.814*** [b]	.662*	—			
4. Orthographic choices, TOC	.705*	.655*	.760**	—		
5. OL recognition	.718**	.117	.355	.469	—	
6. OL spelling	.877*** [b]	.358	.577*	.824*** [b]	.808*** [b]	—

Note. TOWRE = Test of Word Reading Efficiency; C&L = Coltheart and Leahy (1996) reading assessment; TOC = Test of Orthographic Choice; OL = orthographic learning.

**p* < .05. ***p* < .01. ****p* < .001.

[a]Composite score is based on added *z* scores from the nonword decoding tests (TOWRE nonwords + C&L nonwords). [b]Correlation significant also after Bonferroni correction for multiple comparisons (α < .003).

Table 5. Spearman correlations between measures of reading and orthographic learning for typically hearing group.

Measure	1	2	3	4	5	6
1. Nonword decoding composite[a]	—					
2. C&L irregular words	.810*** [b]	—				
3. TOWRE words	.697*** [b]	.503**	—			
4. Orthographic choices, TOC	.546**	.581*** [b]	.394*	—		
5. OL recognition	.362*	.419*	.189	.250	—	
6. OL spelling	.582*** [b]	.445**	.399*	.346*	.683*** [b]	—

Note. Spearman correlations based on *z*-scores. C&L = Coltheart and Leahy (1996) reading assessment; TOWRE = Test of Word Reading Efficiency; TOC = Test of Orthographic Choice; OL = orthographic learning.

*$p < .05$. **$p < .01$. ***$p < .001$.

[a]Composite score is based on added *z*-scores from the nonword decoding tests (TOWRE nonwords + C&L nonwords). [b]Correlation is significant also after Bonferroni correction for multiple comparisons (α < .003).

In the TH group, both visual–verbal and verbal–verbal PAL were significantly correlated with orthographic learning (spelling and recognition) with *r*s above .4.

Summary

The children who are DHH in this study performed below the level of the children with typical hearing on most measures of reading, with the exception of the recognition measure of orthographic learning and orthographic knowledge (TOC). For both the children who are DHH and the TH controls, orthographic learning was correlated with nonword decoding and most measures of stative orthographic reading. Also, orthographic learning (spelling) was moderately to strongly correlated with verbal–verbal and visual–verbal PAL.

Discussion

The aim of the current study was, first, to examine reading ability and orthographic learning in children who are DHH in comparison with a control group of age-matched TH children. The second aim was to examine the cognitive and linguistic factors associated with orthographic learning in children who are DHH and to assess whether they differ from associations observed in TH children.

Group comparisons demonstrated that the children who are DHH performed more poorly than the control group on all reading measures, except for the test of orthographic knowledge (TOC). This result is in line with findings from children with profound hearing loss, which have indicated generally poorer reading skills as compared with TH controls (e.g., Geers, 2003; Geers & Hayes, 2011; Johnson & Goswami, 2010). However, the children who are DHH in the current study had varying degrees of hearing loss, and only 50% of them had a severe–profound hearing loss. In comparison, a group of Swedish children who are DHH with similar degrees of hearing loss within the group did not have general reading skills significantly below the level of hearing controls (Nakeva von Mentzer et al., 2014). These differences in results between studies may reflect differences in language, test measures, or educational practices. The relatively higher performance on the test of orthographic knowledge (TOC), as compared with other reading skills, is in line with previous research, which suggests that orthographic knowledge are relatively intact

Table 6. Spearman correlations between reading and cognitive measures for the deaf or hard of hearing group.

Cognitive/linguistic measure	Phonological decoding measures	Orthographic reading measures			Orthographic learning	
	Nonword decoding composite[a]	C&L irregular words	TOWRE words	TOC	OL recognition	OL spelling
Visual WM	.486	.201	.622*	.282	.504	.285
Visual–visual PAL	.250	.060	.362	.276	.042	.136
Visual–verbal PAL	.078	−.247	.006	.246	.535*	.561*
Verbal–verbal PAL	.669*	.406	.341	.269	.464	.531*
PPVT	.753**	.765**	.627**	.499	.316	.385
RAN	−.226	.116	−.275	−.058	−.544	−.340
Digit span	.293	.249	.418	.495	.257	.530
Segmenting nonwords	.209	.175	.180	.339	.113	.357

Note. None of the correlations were significant after Bonferroni correction for multiple comparisons (α < .001). C&L = Coltheart and Leahy (1996) reading assessment; TOWRE = Test of Word Reading Efficiency; TOC = Test of Orthographic Choice; OL = orthographic learning; WM = working memory; PAL = paired-associate learning; PPVT = Peabody Picture Vocabulary Test; RAN = rapid naming.

*$p < .05$. **$p < .01$.

[a]Composite score is based on added *z* scores from the nonword decoding tests (TOWRE nonwords + C&L nonwords).

Table 7. Spearman correlations between reading and cognitive measures for the typically hearing control group.

Cognitive/linguistic measure	Phonological decoding measures	Orthographic reading measures			Orthographic learning	
	Nonword decoding composite[a]	C&L irregular. words	TOWRE words	TOC	OL recognition	OL spelling
Visual WM	.072	.184	.109	.220	.065	.130
Visual–visual PAL	.283	.285	.279	.353*	.089	.030
Visual–verbal PAL	.473**	.304	.315	.220	.405*	.448**
Verbal–verbal PAL	.480**	.504*	.431*	.423*	.407*	.480**
PPVT	.512**	.668*** [b]	.379*	.569*** [b]	.138	.082
RAN	−.488**	−.408*	−.603*** [b]	−.146	−.017	−.043
Digit span	−.321	.167	.313	.541**	.064	.226
Segmenting nonwords	.349*	.219	.189	−.073	.074	.182

Note. C&L = Coltheart and Leahy (1996) reading assessment; TOWRE = Test of Word Reading Efficiency; TOC = Test of Orthographic Choice; OL = orthographic learning; WM = working memory; PAL = paired-associate learning; PPVT = Peabody Picture Vocabulary Test; RAN = rapid naming.

*$p < .05$. **$p < .01$. ***$p < .001$.

[a]Composite score is based on added *z* scores from the nonword decoding tests (TOWRE nonwords + C&L nonwords). [b]Correlation significant also after Bonferroni correction for multiple comparisons ($\alpha < .001$).

in this group of children (cf. Johnson & Goswami, 2010; Kyle & Harris, 2006; Transler & Reitsma, 2005).

This is, to our knowledge, the first study to investigate orthographic learning in children who are DHH. Given the importance of phonological decoding and spoken vocabulary for orthographic learning in typically developing children (cf. Ehri, 2014; Share, 2004), poorer performance on measures of orthographic learning was expected in the children who are DHH as a consequence of poorer phonological decoding skills (e.g., Johnson & Goswami, 2010; Moeller et al., 2007) and poorer receptive vocabulary (e.g., Moeller et al., 2007; Stiles et al., 2012). Assessment of orthographic learning indeed showed that the children who are DHH achieved lower scores for the spelling measure but not the recognition measure of orthographic learning. Similar to other measures of recognition (cf. Anderson & Bower, 1972; Staresina & Davachi, 2006), the recognition of orthographic representations was less difficult for the children in comparison to spelling, which requires more effortful recall. Recognition has furthermore previously been suggested to be a more sensitive measure of weaker orthographic representations because the weaker representations may be sufficient for recognition but not for spelling (Wang et al., 2011). This result is interesting because it suggests that DHH children can successfully acquire new orthographic representations that are detailed enough for correct recognition after reading the words only a few times.

There were strong correlations between the measures of orthographic learning and phonological reading processes both in children who are DHH and in the TH children in this study. Although the correlational design used here does not allow us to draw conclusions about causality, these results are in line with the self-teaching hypothesis (Share, 1995, 1999), which postulates that phonological decoding is essential for orthographic learning. This model has received strong support from intervention studies where children's orthographic learning is substantially decreased when they are prevented from phonological decoding (Kyte & Johnson, 2006; Share, 1999). It thus seems likely that the self-teaching hypothesis is true not only for typically developing readers (De Jong et al., 2009; Share, 1995, 1999) but also for children who are DHH.

The children who are DHH further had relatively high performance on the standardized measure of preexisting orthographic knowledge, which, besides spelling skills, should be considered the ultimate product of successful orthographic learning (cf. Shahar-Yames & Share, 2008). These findings, together with the relatively high performance on the recognition measure of orthographic learning in this group, would suggest that children who are DHH are able to engage in orthographic learning despite their weak phonological decoding skills.

Both verbal–verbal and visual–verbal PAL measures were significantly correlated with orthographic learning in both groups of children. This result is in line with recent findings from Wang et al. (2017) and supports the view proposed by Ehri (1998, 2014) that the acquisition of new orthographic representations involves arbitrary associations between visual and verbal information. The relationship between verbal–verbal PAL and orthographic learning may reflect the ability to bind and blend verbal information (speech sounds), which, in turn, is fundamental for phonological decoding (see also Litt et al., 2013; Litt & Nation, 2014, for the verbal account of PAL). Interpreted within the multicomponent model of working memory (e.g., Baddeley, 2012), the ability to associate separate pieces of information, whether unimodal as in verbal–verbal PAL tasks or cross-modal as in visual–verbal tasks, would be considered to reflect the capacity to bind information in the episodic buffer before transfer of orthographic information into long-term memory (Allen et al., 2009; Burgess & Hitch, 2005). This basic cognitive skill would thus be important for establishing long-term memory representations of phonological and orthographic representations for children who are DHH and children with typical hearing, irrespective of phonological skill, auditory perception, and reading ability.

In the group of children who are DHH, some correlations with r slightly above .5 were not significant in the current study, for example, between measures of orthographic learning and working memory and rapid naming, respectively. Those correlations should be explored further in a larger sample of DHH children as they may provide some explanations regarding performance in orthographic learning. For example, visual working memory has previously been reported to predict orthographic knowledge in children who are DHH (Johnson & Goswami, 2010), and in the current study, the correlation between reading fluency (TOWRE) and visual working memory was significant. It is therefore possible, as suggested by Johnson and Goswami (2010), that visual working memory plays a special role in the development of reading skills for children who are DHH, particularly for their development of orthographic knowledge.

The main limitation of this study is the heterogeneity and relatively low number of participants in the DHH group, which does not allow for analyses of the unique contributions of the various predictors of reading and orthographic learning while holding others constant. On the other hand, such homogeneity of participants and large samples is rare in research on children who are DHH. Also, it would have been interesting to include more assessments to follow up, for example, on children's retention of written words from the orthographic learning tasks and other language measures such as spelling skills. However, we needed to prioritize among the number of tests in order to keep the test sessions reasonably short for the children. In particular, the children who are DHH go through a number of clinical assessments regularly, and the test times were set with consideration to the children and their families.

Some of the cognitive and linguistic measures used in this study involve auditory presentation of test items. Auditory presentation may have a negative effect on the performance of DHH children even though all efforts were made to ensure that they could perceive the test items correctly, for example, by having them repeat spoken stimuli before responding. For DHH children, performance in audio–verbal tasks may certainly be influenced by both hearing and the variable of interest. Still, these measures are considered to be important in typical reading acquisition, making it important to discover whether similar cognitive skills are also relevant to reading development in children with hearing loss.

Overall, the children who are DHH in the current study performed below the level of peers with typical hearing and typical reading development on most of the measures of reading used in this study. Their performance was also below TH peers on the spelling measure but not on the recognition measure of orthographic learning, which suggests that children who are DHH are able to acquire orthographic representations from a brief exposure to words, although these representations may, at least initially, be weaker than for TH children. Based on the current results, it is likely that problems with orthographic learning in children who are DHH are a consequence of poor phonological decoding. It is further likely that these difficulties may result in the previously reported drop in reading development as children who are DHH grow older (Geers & Hayes, 2011; Harris & Terlektsi, 2010), and this issue should be further investigated in future research. The cognitive variables associated with orthographic learning in this study were relatively similar to those for children with typical hearing, including orthographic knowledge and PAL.

The results from the current study suggest that phonological decoding may be the key to fluent reading also in children who are DHH. Thus, efforts should be made to give educational support, specifically aimed at improving phonological decoding in this group of children. The finding that children who are DHH do develop orthographic representations that are sufficiently distinct for recognition tasks but not for spelling further suggests that they may need more practice for successful orthographic learning to occur. Future research should investigate what methods, for example, quiet reading, reading aloud, or spelling, would be most efficient in supporting children who are DHH to learn new orthographic representations. This type of knowledge would be important for reading development in this group of children and for theories of orthographic learning in general.

Acknowledgments

This project was funded by the Swedish Research Agency for Health, Working Life and Welfare, and the European Commission through a COFAS Marie Curie Fellowship to the first author. The work was carried out as part of the Longitudinal Outcomes of Children with Hearing Impairment study, supported by the National Institute on Deafness and Communication Disorders Award No. R01DC008080. The project was also partly supported by the Commonwealth of Australia through the Office of Hearing Services. We acknowledge the financial support of the HEARing Cooperative Research Centre, established and supported under the Cooperative Research Centres Program of the Australian Government. We are grateful to the pupils, parents, and teachers of the schools that participated in the project. We also thank the researchers and staff at the Department of Cognitive Science and the Centre of Excellence in Cognition and its Disorders, Macquarie University, and the National Acoustic Laboratories for their advice and support during the data collection phase of the project.

References

Allen, R. J., Hitch, G. J., & Baddeley, A. D. (2009). Cross-modal binding and working memory. *Visual Cognition, 17,* 83–102.

Anderson, J. R., & Bower, G. H. (1972). Recognition and retrieval processes in free recall. *Psychological Review, 79,* 97–123.

Anthony, J. L., & Francis, D. J. (2005). Development of phonological awareness. *Current Directions in Psychological Science, 14,* 255–259.

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63,* 1–29.

Bender, R., & Lange, S. (2001). Adjusting for multiple testing—When and how? *Journal of Clinical Epidemiology, 54,* 343–349.

Bowey, J. A., & Muller, D. (2005). Phonological recoding and rapid orthographic learning in third-graders' silent reading: A critical test of the self-teaching hypothesis. *Journal of Experimental Child Psychology, 92*(3), 203–219.

Brown, C. A., & Bacon, S. P. (2010). Fundamental frequency and speech intelligibility in background noise. *Hearing Research, 266,* 52–59.

Burgess, N., & Hitch, G. (2005). Computational models of working memory: Putting long-term memory into context. *Trends in Cognitive Sciences, 9,* 535–541.

Byrne, B., Coventry, W. L., Olson, R. K., Hulslander, J., Wadsworth, S., DeFries, J. C., . . . Samuelsson, S. (2008). A behaviour-genetic analysis of orthographic learning, spelling and decoding. *Journal of Research in Reading, 31,* 8–21.

Castles, A., Coltheart, M., Larsen, L., Jones, P., Saunders, S., & McArthur, G. (2009). Assessing the basic components of reading: A revision of the Castles and Coltheart test with new norms. *Australian Journal of Learning Difficulties, 14*(1), 67–88.

Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology, 97,* 165–182.

Ching, T. Y. C., Leigh, G., & Dillon, H. (2013). Introduction to the Longitudinal Outcomes of Children with Hearing Impairment (LOCHI) study: Background, design, sample characteristics. *International Journal of Audiology, 52,* 4S–9S.

Coltheart, M., & Leahy, J. (1996). Assessment of lexical and nonlexical reading abilities in children: Some normative data. *Australian Journal of Psychology, 48,* 136–140.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). A dual route cascaded model of word recognition and reading aloud. *Psychological Review, 108,* 204–256.

Cunningham, A. E. (2006). Accounting for children's orthographic learning while reading text: Do children self-teach? *Journal of Experimental Child Psychology, 95*(1), 56–77.

Cunningham, A. E., Perry, K. E., Stanovich, K. E., & Share, D. L. (2002). Orthographic learning during reading: Examining the role of self-teaching. *Journal of Experimental Child Psychology, 82,* 185–199.

De Jong, P. F., Bitter, D. J. L., van Setten, M., & Marinus, E. (2009). Does phonological recoding occur during silent reading and is it necessary for orthographic learning? *Journal of Experimental Child Psychology, 104,* 267–282.

Dunn, L. M., & Dunn, D. M. (2007). *Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4)*. Bloomington, MN: NCS Pearson.

Ehri, L. C. (1992). Reconceptualizing the development of sight word reading and its relationship to recoding. In P. Gough, L. Ehri, & R. Treiman (Eds.), *Reading acquisition* (pp. 107–143). Hillsdale, NJ: Erlbaum.

Ehri, L. C. (1998). Grapheme–phoneme knowledge is essential for learning to read words in English. In J. Metsala & L. Ehri (Eds.), *Word recognition in beginning literacy* (pp. 3–40). Mahwah, NJ: Erlbaum.

Ehri, L. C. (2005). Learning to read words: Theory, findings, and issues. *Scientific Studies of Reading, 9,* 167–188.

Ehri, L. C. (2014). Orthographic mapping in the acquisition of sight word reading, spelling memory, and vocabulary learning. *Scientific Studies of Reading, 18,* 5–21.

Elliott, C. D., Smith, P., & McCulloch, K. (1996). *British Ability Scales–Second Edition (BAS II)*. Windsor, England: NferNelson, 1996.

Fagan, M. K., & Pisoni, D. B. (2010). Hearing experience and receptive vocabulary development in deaf children with cochlear implants. *Journal of Deaf Studies and Deaf Education, 15*(2), 149–161.

Gathercole, S. E. (2006). Nonword repetition and word learning: The nature of the relationship. *Applied Psycholinguistics, 27,* 513–543.

Geers, A. E. (2003). Predictors of reading skill development in children with early cochlear implantation. *Ear and Hearing, 24,* 59S–68S.

Geers, A. E., & Hayes, H. (2011). Reading, writing, and phonological processing skills of adolescents with 10 or more years of cochlear implant experience. *Ear and Hearing, 32*(1), 49S–59S.

Geers, A. E., Moog, J. S., Biedenstein, J., Brenner, C., & Hayes, H. (2009). Spoken language scores of children using cochlear implants compared to hearing age-mates at school entry. *Journal of Deaf Studies and Deaf Education, 14*(3), 371–385.

Goswami, U., Wang, H. L., Cruz, A., Fosker, T., Mead, N., & Huss, N. (2010). Language-universal sensory deficits in developmental dyslexia: English, Spanish, and Chinese. *Journal of Cognitive Neuroscience, 23*(2), 325–337.

Harris, M., & Terlektsi, E. (2010). Reading and spelling abilities of deaf adolescents with cochlear implants and hearing aids. *Journal of Deaf Studies and Deaf Education, 16*(1), 24–34.

Hulme, C., Bowyer-Crane, C., Carroll, J. M., Duff, F. J., & Snowling, M. J. (2012). The causal role of phoneme awareness and letter–sound knowledge in learning to read: Combining intervention studies with mediation analyses. *Psychological Science, 23*(6), 572–577.

Hulme, C., Goetz, K., Gooch, D., Adams, J., & Snowling, M. J. (2007). Paired-associate learning, phoneme awareness, and learning to read. *Journal of Experimental Child Psychology, 96,* 150–166.

Johnson, C., & Goswami, U. (2010). Phonological awareness, vocabulary, and reading in deaf children with cochlear implants. *Journal of Speech, Language, and Hearing Research, 53,* 237–261.

Kohnen, S., Anandakumar, T., McArthur, G., & Castles, A. (2012). *The Test of Orthographic Choice (TOC)*. Retrieved from http://www.motif.org.au

Kohnen, S., Nickels, L., & Castles, A. (2009). Assessing spelling skills and strategies: A critique of available resources. *Australian Journal of Learning Difficulties, 14*(1), 113–150. https://doi.org/10.1080/19404150902783450

Kyle, F. E., & Harris, M. (2006). Concurrent correlates and predictors of reading and spelling achievement in deaf and hearing school children. *Journal of Deaf Studies and Deaf Education, 11*(3), 273–288.

Kyte, C. S., & Johnson, C. J. (2006). The role of phonological recoding in orthographic learning. *Journal of Experimental Child Psychology, 93,* 166–185.

Landi, N., Perfetti, C. A., Bolger, D. J., Dunlap, S., & Foorman, B. R. (2006). The role of discourse context in developing word form representations. A paradoxical relation between reading and learning. *Journal of Experimental Child Psychology, 94,* 114–133.

Lervåg, A., Bråten, I., & Hulme, C. (2009). The cognitive and linguistic foundations of early reading development: A Norwegian latent variable longitudinal study. *Developmental Psychology, 45*(3), 764–781.

Leybaert, J. (2007). Learning to read with a hearing impairment. In M. J. Snowlin & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 379–396). Malden, MA: Blackwell.

Litt, R. A., De Jong, P. F., Van Bergen, E., & Nation, K. (2013). Dissociating crossmodal and verbal demands in paired associate learning (PAL): What drives the PAL-reading relationship? *Journal of Experimental Child Psychology, 115,* 137–149.

Litt, R. A., & Nation, K. (2014). The nature and specificity of paired associate learning deficits in children with dyslexia. *Journal of Memory and Language, 71,* 71–88.

Lyxell, B., Sahlén, B., Wass, M., Ibertsson, T., Larsby, B., Hällgren, M., & Mäki-Torkko, E. (2008). Cognitive development in children

with cochlear implants: Relations to reading and communication. *International Journal of Audiology, 47*(S2), S47–S52.

Marinus, E., Kohnen, S., & McArthur, G. (2013). Australian comparison data for the Test of Word Reading Efficiency (TOWRE). *Australian Journal of Learning Difficulties, 18,* 199–212.

Masterson, J., Stuart, M., Dixon, M., Lovejoy, D., & Lovejoy, S. (2003). *The Children's Printed Word Database*. Colchester, England: Department of Psychology, University of Essex.

Messbauer, V. C. S., & De Jong, P. F. (2003). Word, nonword, and visual paired associate learning in Dutch dyslexic children. *Journal of Experimental Child Psychology, 84*(2), 77–96.

Miller-Guron, L. (1999). *Wordchains: A word reading test for all ages*. Windsor, England: NferNelson.

Moeller, M. P., Tomblin, J. B., Yoshinaga-Itano, C., McDonald Connor, C., & Jerger, S. (2007). Current state of knowledge: Language and literacy of children with hearing impairment. *Ear and Hearing, 28*(6), 740–753.

Nakeva von Mentzer, C., Lyxell, B., Sahlén, B., Dahlström, Ö., Lindgren, M., Ors, M., . . . Uhlén, I. (2014). Computer-assisted reading intervention with a phonics approach for children using cochlear implants or hearing aids. *Scandinavian Journal of Psychology, 55,* 448–455.

Nation, K., Angell, P., & Castles, A. (2007). Orthographic learning via self-teaching in children learning to read English: Effects of exposure, durability, and context. *Journal of Experimental Child Psychology, 96*(1), 71–84.

Nation, K., & Castles, A. (2017). Putting the learning in orthographic learning. In K. Cain, D. Compton, & R. Parilla (Eds.), *Theories of reading development* (pp. 147–168). Amsterdam, the Netherlands: John Benjamins.

Perneger, T. V. (1998). What's wrong with Bonferroni adjustments. *British Medical Journal, 316,* 1236–1238.

Pisoni, D. B., Conway, C. M., Kronenberger, W. G., Horn, D. L., Karpicke, J., & Henning, S. (2008). Efficacy and effectiveness of cochlear implants in deaf children. In: M. Marschark & P. Hauser (Eds.), *Deaf cognition: Foundations and outcomes* (pp. 52–101). New York, NY: Oxford University Press.

Rau, A. K., Moeller, K., & Landerl, K. (2014). The transition from sublexical to lexical processing in a consistent orthography: An eye-tracking study. *Scientific Studies of Reading, 18,* 224–233.

Shahar-Yames, D., & Share, D. L. (2008). Spelling as a self-teaching mechanism in orthographic learning. *Journal of Research in Reading, 31,* 22–39.

Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition, 55*(2), 151–218.

Share, D. L. (1999). Phonological recoding and orthographic learning: A direct test of the self-teaching hypothesis. *Journal of Experimental Child Psychology, 72,* 95–129.

Share, D. L. (2004). Orthographic learning at a glance: On the time course and developmental onset of self-teaching. *Journal of Experimental Child Psychology, 87,* 267–298.

Staresina, B. P., & Davachi, L. (2006). Differential encoding mechanisms for subsequent associative recognition and free recall. *The Journal of Neuroscience, 26,* 9162–9172.

Stiles, D. J., McGregor, K. K., & Bentler, R. A. (2012). Vocabulary and working memory in children fit with hearing aids. *Journal of Speech, Language, and Hearing Research, 55,* 154–167.

Tomblin, J. B., Harrison, M., Ambrose, S. E., Walker, E. A., Oleson, J. J., & Moeller, M. P. (2015). Language outcomes in young children with mild to severe hearing loss. *Ear and Hearing, 36*(Suppl. 1), 76S–91S.

Transler, C., & Reitsma, P. (2005). Phonological coding in reading of deaf children: Pseudohomophone effects in lexical decision. *British Journal of Developmental Psychology, 23,* 525–542.

Vanderplas, J. M., & Garvin, E. A. (1959). The association value of random shapes. *Journal of Experimental Psychology, 57,* 147–154.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *Comprehensive Test of Phonological Processing (CTOPP)*. Oxford, United Kingdom: Pearson.

Wang, H. C., Castles, A., Nickels, L., & Nation, K. (2011). Context effects on orthographic learning of regular and irregular words. *Journal of Experimental Child Psychology, 109*(1), 39–57.

Wang, H. C., Wass, M., & Castles, A. (2017). Paired-associate learning ability accounts for unique variance in orthographic learning. *Scientific Studies of Reading, 21*(1), 5–16. https://doi.org/10.1080/10888438.2016.1231686

Wass, M., Ibertsson, T., Lyxell, B., Sahlén, B., Hällgren, M., Larsby, B., & Mäki-Torkko, E. (2008). Cognitive and linguistic skills in Swedish children with cochlear implants—Measures of accuracy and latency as indicators of development. *Scandinavian Journal of Psychology, 49,* 559–576.

Wegener, S., Wang, H. C., de Lissa, P., Robidoux, S., Nation, K., & Castles, A. (2018). Children reading spoken words: Interactions between vocabulary and orthographic expectancy. *Developmental Science, 21,* 1–9.

Appendix

Glossary

nonword	A made-up word that may or may not sound like a real word.
homophone	A word with the same pronunciation as another word, but with a different spelling, for example, *toad-towed*.
pseudohomophone	A nonword, which is pronounced exactly like a real word if read by phonological decoding, for example, *tode* is a pseudohomophone of the word *toad*.
digraph	A phoneme represented by two letters, for example, the English phoneme /th/ in “the.”