Phonological processing during silent reading in teenagers who are deaf/hard of hearing: An eye movement investigation

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Highlights

- In their global eye movement behaviour during silent sentence reading, teenagers with permanent childhood hearing loss (PCHL) showed evidence of a developmental delay in their reading ability when compared to both reading age-matched (WRA) and chronological age-matched (CA) control groups of hearing peers.
- In their reading behaviour on target words/ nonwords, teenagers with PCHL showed a pseudohomophone advantage in both foveal processing and parafoveal pre-processing that was comparable to the effect in both CA and WRA control groups.
- These data provide strong evidence for phonological recoding during lexical identification during silent sentence reading in teenagers with PCHL, despite their broader reading difficulties.

Abstract

There has been considerable variability within the literature concerning the extent to which deaf/ hard of hearing individuals are able to process phonological codes during reading. Two experiments are reported in which participants' eye movements were recorded as they read sentences containing correctly spelled words (e.g., church), pseudohomophones (e.g., cherch), and spelling controls (e.g., charch). We examined both foveal processing and parafoveal pre-processing of phonology for three participant groups – teenagers with permanent childhood hearing loss (PCHL), chronological age-matched controls, and reading age-matched controls. The teenagers with PCHL showed a pseudohomophone advantage from both directly fixated words and parafoveal preview, similar to their hearing peers. These data provide strong evidence for phonological recoding during silent reading in teenagers with PCHL.

Introduction

In the vast majority of cases, an individual learns to speak before they learn to read. Typical literacy acquisition can, therefore, be characterised as a mapping process in which orthographic forms become associated with existing lexical entries that contain both phonological and semantic information (Frost, 1998). In this way, the representation and processing of phonology is fundamental to literacy acquisition. When reading silently, a significant body of research has demonstrated that adults activate phonological codes for the words that they are reading, despite the fact that the task contains no direct requirement for phonological processing. Furthermore, this phonological processing is pre-lexical such that it facilitates activation of the word's entry in the mental lexicon (for a recent review, see Leinenger, 2014). Much less consistent, however, is the evidence for phonological coding during reading in readers who are deaf or hard of hearing (Mayberry, del Giudice, & Lieberman, 2010). In the present study, we examined the extent to which deaf teenagers were able to process phonological cues when reading silently, from words both in foveal and parafoveal vision, in comparison to both chronological age- and word reading age-matched control groups.

A wide range of experimental paradigms have been used to investigate the role of phonological codes in lexical identification, and there has been debate over the extent to which different paradigms may or may not reflect pre-lexical processing of phonology (Leinenger, 2014). A significant portion of the evidence for pre-lexical phonological coding during reading has come from studies in which readers' eye movements were recorded as they read sentences containing a target word. In these studies, the target words/nonwords are typically manipulated in terms of their phonological and orthographic overlap with a correct word that fits within the sentence context, and reading times on the phonologically/ orthographically related but incorrect words/nonwords are examined to indicate the cost associated with activating the correct lexical entry based on the cues available. Rayner, Pollatsek, and Binder (1998) found greater facilitation to processing from phonological cues when the orthographic overlap between a homophone and its mate was high (e.g., *break-brake*) relative to when there was little orthographic overlap (e.g., *chute-shoot*) (Experiment 1). Such facilitated processing did not occur from words that shared the same degree of orthographic overlap with the correct target but did not share phonological cues (Experiments 2 and 3). The data reported by Rayner et al. show, therefore, early processing of phonological cues in lexical identification that is, to some extent, dependent upon orthographic overlap.

When combined with evidence from other studies, it seems likely that such early processing of phonological cues is pre-lexical. A substantial body of research has shown that readers are able to pre-process information from the next word in the sentence (referred to as word n+1) during fixations on the current word (referred to as word n) (see Rayner, 2009, for a review). This is referred to as parafoveal pre-processing. Such processing is pre-lexical, in that it precedes lexical identification, and facilitates subsequent lexical identification of the word once it is directly fixated. Parafoveal pre-processing is typically studied using the boundary paradigm (Rayner, 1975), in which a participant's eye movements are recorded as they silently read a sentence containing a target word. An invisible boundary is placed in the space before the target word. Prior to the reader's eyes crossing that boundary, a preview letter string is presented in the target word location; once the reader's eyes cross the boundary (e.g., once they directly fixate the target location) then the preview letter string is replaced with the correct target word. By manipulating the relationship between the preview letter string and the correct target word (e.g., shared phonological or orthographic codes) then the researcher can infer whether or not those manipulated characteristics were pre-processed during fixations on the prior word in the sentence. If the preview and the target share some linguistic characteristic, then processing of the target would be facilitated such that fixations on it would be shorter than those following an unrelated, control, preview. This facilitation is referred to as preview benefit. Using the boundary paradigm, Pollatsek *et al.* found that English readers pre-process phonological cues from the upcoming word in the sentence before going on to directly fixate that word (Pollatsek, Lesch, Morris, & Rayner, 1992; though see Tiffin-Richards & Schroeder, 2015, for data from readers of a regular orthography). This result strongly suggests that readers were processing phonological cues for a word prior to lexical identification; however, parafoveal pre-processing of phonology is linked to reading ability and only occurs in more skilled readers (Chace, Rayner, & Well, 2005). On the basis of these key studies that studied sentence reading, alongside many more from other experimental paradigms such as isolated word recognition, it is now widely accepted that skilled adult readers activate phonological codes pre-lexically as part of word identification.

More recently, such effects have been demonstrated in children's reading from a range of experimental paradigms (e.g., Jared, Ashby, Agauas, & Levy, 2015). It is well-known that phonological decoding is a vital phase of early literacy acquisition (e.g., Ehri, 2005; Frost, 1998; Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001; Share, 1995). As literacy skill increases, a beginning reader must progress from phonological decoding (the conscious, effortful process of sounding out words, either overtly or covertly) to phonological recoding (the subconscious activation of abstract phonological codes) (Frost, 1998). Preliminary evidence for phonological recoding in children as young as 7-years old during silent sentence reading was reported by Blythe, Pagan, and Dodd (2015). Children showed a pseudohomophone advantage – faster reading of pseudohomophones than matched spelling controls – that was equivalent to the effect observed in the skilled adult readers. Thus, it appears that phonological recoding during silent sentence reading emerges quite early in literacy development.

It is well-established that many individuals who are deaf/ hard of hearing experience substantial difficulties in learning to read (e.g., Conrad, 1979), and there is an extensive published literature that documents the investigation of a number of underlying/ predicting factors for these reading difficulties (see Kyle, Campbell, & MacSweeney, 2016, for a review). There has been a significant degree of debate within the published literature concerning the extent to which deaf and hard of hearing readers activate phonological codes during reading (see Mayberry, del Giudice, & Lieberman, 2010, for a review). Much of this research, however, has used relatively artificial experimental paradigms such as isolated word recognition tasks (see Rayner & Liversedge, 2011, for a discussion of how such tasks may not necessarily reflect the cognitive processing associated with normal reading), or tasks that require some degree of explicit processing of phonology such as making rhyme judgements (which, again, may not reflect more typical silent reading). Interestingly, recent work has recorded the eye movements of deaf readers to investigate their cognitive processing during a relatively natural, silent sentence reading task (Bélanger, Mayberry, & Rayner, 2013; Bélanger, Slattery, Mayberry, & Rayner, 2012). Eye movement recordings are a sensitive index of the moment-to-moment cognitive processing that underlies reading (Liversedge & Findlay, 2000). This technique has been widely used to study skilled reading as well as both typical and atypical reading development (see Rayner, 1998, 2009; and Blythe, 2014, for reviews). The studies by Bélanger et al. have investigated the extent to which deaf readers were able to pre-process information from upcoming words within a sentence, prior to those words being directly fixated (using gaze-contingent techniques such as the boundary paradigm). The results showed that: (1) skilled deaf readers have a wider perceptual span than their hearing counterparts (Bélanger *et al.*, 2012); (2) both skilled and less skilled deaf readers pre-process orthographic information from upcoming words (Bélanger *et al.*, 2013); and (3) neither skilled nor less skilled deaf readers pre-process phonological information from upcoming words (Bélanger *et al.*, 2013). Importantly, the participants in these studies were all severely to profoundly deaf (a hearing loss of at least 71 dB SPl in the better ear), and used sign language as their primary mode of communication. Whilst it seems inevitable that a hearing loss will result in relative under-specification of phonology within the mental lexicon, it seems unlikely that, for the majority of individuals with hearing loss, the representation and processing of phonology would be completely absent. Indeed, many researchers have suggested that an individual's residual/ aided hearing, as well as other sources of information such as lip-reading and manual gestures that represent spoken phonology, might still allow for the instantiation of phonological representations that are activated during reading (Mayberry, del Giudice, & Lieberman, 2010). Furthermore, in the Bélanger *et al.* studies, the control groups were skilled adult readers with normal hearing levels. Here, two control groups were included - one group who were matched to the deaf/hard of hearing readers in their chronological age, and a second group who were matched in their word reading ability. These two control groups offer the opportunity to examine whether any differences in processing orthography and phonology might be due to either delayed or atypical literacy development.

In the present study, we examined both foveal and parafoveal pre-processing of orthography and phonology in a sample of deaf/ hard of hearing readers who varied in both their level of hearing loss, and in their use of oral and/or sign language. In order to identify a printed word, the reader must access the lexical representation from the orthographic input. As discussed, it is widely accepted that typically developing readers activate phonological codes from the orthographic input prior to accessing the lexical representation containing semantic information. By manipulating the phonological and orthographic features of the printed stimuli, we examined: (1) the extent to which deaf/ hard of hearing readers are able to process these two sources of information in order to activate lexical representations during reading; and (2) whether any phonological recoding that might be observed would be interactive with, or independent from, concurrent orthographic processing. There were three participant groups: teenagers with permanent childhood hearing loss (PCHL); chronological age-matched controls (CA controls); and word reading age-matched controls (WRA controls). In both experiments, participants' eye movements were recorded as they silently read sentences containing target words for which two manipulations were made: (1) phonological similarity; and (2) orthographic similarity. Target words were either correctly spelled (e.g., *church*), a pseudohomophone (e.g., *cherch*), or a spelling control (e.g., *charch*); furthermore, the nonwords (pseudohomophones and spelling controls) were either orthographically similar or dissimilar to their correctly spelled base word. In Experiment 1, these target words/nonwords were presented within meaningful sentence frames and we analysed reading times on those target words/nonwords across the three participant groups in order to examine foveal processing of phonology and orthography. For Experiment 1, we made four predictions. First, that overall reading times would be similar in the teenagers with PCHL and their reading age-matched controls, but they would be shorter (indicating reduced processing difficulty) in the chronological age-matched controls. Such a pattern would reflect the well-known reading difficulties associated with hearing impairment (e.g., Kelly & Barac-Cikoja, 207; McCann *et al.*, 2008; Pimperton *et al.*, 2016), as well as demonstrating the efficacy of our reading age-matching procedure. Second, that all participants would show shorter reading times on nonwords when they were orthographically similar to their correctly spelled base word than when they were orthographically dissimilar. Third, that both groups of hearing readers would show shorter reading times on pseudohomophones than on spelling controls (a pseudohomophone advantage), reflecting their activation of phonological codes during lexical identification. Fourth, that readers with PCHL would show a reduced pseudohomophone advantage, if at all, due to having under-specified representations of phonology within the mental lexicon.

Stimuli pre-screening

In order to prepare stimuli for the two eye movement experiments, it was first necessary to pre-screen those stimuli in order to ensure, insofar as possible, that: (1) with the support of the sentence context, the readers would be able to identify what the correctly spelled target word should be in the nonword conditions; and (2) the weakest readers who would be included in the main eye movement studies would be able to read and comprehend the sentence stimuli.

Method.

Participants. Seventy eight children aged 8- to 9-years, who did not take part in the subsequent eye movement experiments. All participants attended one of three local primary schools, took part on a voluntary basis, and had no known hearing impairment or reading difficulties.

Materials and design. An initial list of 48 4-6 letter target words was generated. For each target word, four sentence frames were constructed. Two tasks were used in this pre-screening experiment. Task 1 was sentence constraint rating. Participants were given the sentence context with a blank space in the location of the target word, and were asked to fill in the word that best completed the sentence. Task 2 was sentence difficult rating. Participants were presented with the complete sentences and were asked to rate each one on a scale of 1 (easy) to 7 (difficult) for how they found that sentence to read.

As each target word had four possible sentence frames, there were 192 sentences in total – too many for any individual child to read and rate. They were, therefore, split into two lists, with two sentence frames per target word on each list. Each child only completed one of the two tasks, and the tasks were administered on a class-by-class basis. Given the time constraints associated with collecting data in a classroom, we knew it was likely that not all children would complete their task, and so three different versions of each list were created, so that the same items appeared but in different, randomised orders, ensuring that those appearing toward the end of the list were varied. For this reason, the number of children rating each sentence, and on each task, ranged between eight and 19.

Procedure. All data were collected in the classroom. The experimenter explained the task and talked through a couple of examples, giving the children opportunity to ask questions. Hard copies of the questionnaires were then handed out. The two lists of stimuli were distributed in alternation so that no child was sat next to another child with the same stimuli.

Results. Sentence constraint rating task. Individual sentence scores ranged from 0% to 100%. A sentence frame was only considered for inclusion in the stimulus set for the eye movement experiments if at least 60% of the children predicted that word from the sentence context. Sentence comprehension rating task. The individual sentence mean scores ranged from 1.00 to 2.44. An item was only considered for inclusion in the final stimulus set if its mean difficulty rating was less than or equal to 2.00 (on a scale of 1-7). Using these criteria, we selected a final stimulus set of 24 target words, with two sentence frames per target word. Half of these sentence frames were used in Experiment 1, and the other half were used in Experiment 2.

Experiment 1

Method.

Participants. There were three participant groups, with 23 participants in each – teenagers with permanent childhood hearing loss (PCHL); chronological age-matched controls (CA controls); and word reading age-matched controls (WRA controls). The teenagers with PCHL were aged 17-21 years with a hearing loss ranging from moderate (29-39 dB HL) to profound (≥ 95 dB HL) that was not known to be postnatally acquired. Severity of hearing loss was calculated from the most recent audiological evaluation as a four-frequency averaging of the pure-tone thresholds at 0.5, 1, 2, and 4 kHz, and ranged from 40 to 130 dB HL. A number of participants with PCHL were BSL-English bilinguals, but all were able to communicate with the research team orally and through lip-reading.

All participants in both the CA and WRA control groups had normal hearing. The CA control group was matched to the PCHL group on chronological age and IQ. The WRA control group was matched to the PCHL group on word reading ability and IQ.

For all participants, we completed a number of cognitive assessments (see Table 1 for a summary).

Insert Table 1 about here.

The CA control group performed significantly better than the PCHL group on standardized assessments of word reading, pseudoword decoding, phonological processing, and vocabulary, despite being matched on age and IQ. The WRA control group were significantly younger than the PCHL group, and also performed significantly better on pseudoword decoding, phonological processing, and vocabulary, despite being matched on their word reading ability[1] and IQ. Note that this pattern of differences between the PCHL group and the WRA group was entirely expected; if the WRA group had achieved lower scores on standardised assessments of phonological processing, pseudoword decoding, or vocabulary, then this would have indicated atypical development in those areas. Our aim here was to recruit a typically developing group, necessarily younger in age, who were matched to the PCHL group on their word reading ability.

Apparatus. Word reading and pseudoword decoding were measured with the relevant subtests of the Wechsler Individual Achievement Test (2nd edition; WIAT-II; Wechsler, 2005). Phonological processing was measured with the Elision and Blending Words subtests of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen & Rashotte, 1999).[2] Receptive vocabulary was measured with the British Picture Vocabulary Scale (BPVS; Dunn & Dunn, 2009). Nonverbal IQ was measured with Raven's Standard Progressive Matrices (Raven, Court, & Raven, 1998).[3]

Eye movements were recorded using an EyeLink 1000 (SR Research Ltd.). Chin and forehead rests were used to minimise head movements. Viewing was binocular, but only movements of the right eye were recorded. Stimuli were presented in Courier New size 14 font, on a 21” ViewSonic CRT monitor, with a refresh rate of 100Hz (120 Hz for two participants) at a viewing distance of 60 cm. Participants’ button press responses were recorded with a Microsoft gamepad.

Materials and Design. The materials were based on the set of 24 target words and sentence frames that were selected on the basis of the pre-screening experiment. Two manipulations were made within this stimulus set – a within-item phonological manipulation, and a between-item orthographic manipulation. With respect to the phonological manipulation, for each target word we created two nonwords to form a target word/nonword triplet – the correctly spelled word, a pseudohomophone, and a spelling control (e.g., *church*/*cherch*/*charch*). All nonwords were orthographically legal and were pronounceable. The length of the target word/nonwords was always perfectly matched within each triplet, and syllabic structure was maintained. The pseudohomophones and spelling controls were matched on: (1) orthographic overlap with the correctly spelled target, for both the number and within-word positions of the substituted letters; (2) number of neighbours (defined as the number of real words that could be formed by making a single, position-specific letter substitution) (t_1 (23) = 0.72, p = 0.48); (3) consonant-vowel structure; (4) word shape (e.g., ascenders were replaced with ascenders, descenders with descenders, etc.).

With respect to the orthographic manipulation, each target triplet was categorized as being orthographically similar (12 target triplets) or dissimilar (12 target triplets). For orthographically similar triplets only one letter was substituted to form the two nonwords (e.g., *church/cherch/charch*), and this substituted letter was never the first or second letter of the word. For orthographically dissimilar triplets at least two letters were substituted to form the two nonwords (e.g., *ball/borl/bewl*), and at least one of these substitutions affected the first and/or second letter of the word. The two sets of correctly spelled target words that were generated on the basis of this between-item split (12 in each condition) were matched on the following variables: frequency count from an adult corpus (0 – 1882 per million; Balota et al., 2007); frequency count from a child corpus (8-560 per million; Masterson, Dixon & Stuart, 2003); Age of Acquisition (150-358; Kuperman, Stadthagen-Gonzalez & Brysbaert, 2012); and their orthographic neighbourhood size (0-23 neighbours) (all *t*s < 2, all *p*s > 0.1). There was a marginally significant difference in word length; whilst both sets contained target words that were between 4 and 6 letters, the orthographically similar words had a mean length of 5.33 letters whilst for the dissimilar words the mean length was 4.67 letters (t_1 (22) = 2.10, p = 0.05). The full set of experimental stimuli is provided in the Appendix.

Three counterbalanced lists of sentences were created, each including one target word/nonword from every triplet: four correctly spelled targets, four pseudohomophones, and four spelling controls from the orthographically similar stimuli, and the same from the orthographically dissimilar stimuli. Thus, there was no repetition within the stimuli for any participant, but each participant contributed data to all experimental conditions.

After 25% of sentences participants were presented with a yes/no comprehension question, to which they responded by pressing one of two keys on the gamepad. After 50% of the sentences containing nonwords targets (33% of the total number of sentences read), participants were presented with a forced-choice target test question, to which they responded using one of two keys on the gamepad: *"In that sentence, there was a word that was not spelled correctly. That word was XXXX (nonword from preceding trial inserted here). Which of the two words below do you think it* *should have been?"* Two words were then presented – the correctly spelled target word, and a real word distractor that was matched to the target in length, and that was matched to the pseudohomophones and spelling controls in terms of the number and location(s) of letters that differed from the correct target word (e.g., for the correct target word *nose*, the third letter was changed to form *noze, nove*, and *none* – pseudohomophone, spelling control, and distractor word, respectively).

Procedure. Participants first completed the eye movement experiment. They were seated comfortably, and then a 3-point horizontal calibration and validation procedure was carried out. If the mean validation error, or the error for any one of the points individually, was greater than 0.2 deg, then the procedure was repeated. The first five trials were practice trials, with one target test trial and one comprehension question trial, to ensure that participants were familiar with the procedure. Participants were presented with a single sentence at a time, and were instructed to read it silently and press a button on the gamepad once they had finished. They were told that some of the words might be misspelled, but they should just do their best to understand the sentences. The eye movement experiment component lasted approximately 15 minutes per participant.

After the eye movement experiment each participant then completed the word reading and pseudoword decoding subtests of the WIAT-II, the elision and blending words subtests of the CTOPP, and the BPVS. These assessments lasted approximately 30 minutes. Participants then completed a second eye movement experiment (see Experiment 2, approximately 15 minutes in duration), before finishing the test session by completing a 20-minute timed version of the SPM+.

Results.

All participants scored at least 67% correct on the comprehension questions (67%-100%; mean = 91%), and at least 88% correct on the target test questions (88%-100%; mean = 99%). One-way ANOVAs showed that there were no group differences on either measure (*F*s < 3, *p*s > 0.1). The data were trimmed using the clean function in DataViewer (SR Research).[4] In total, 1191 fixations were merged/deleted (2.9% of the dataset).

We examined reading time data on the target word/nonword in each sentence. These data were analysed using linear mixed effects (lme) models (Bates, Maechler & Dai, 2009) within the R environment for Statistical Computing (R Development Core Team, 2009), with participants and items entered as crossed random effects. We initially specified a full random structure for participants and items, to avoid being anti-conservative (Barr, Levy, Scheepers & Tily, 2013); for each dependent measure, if the initial model failed to converge then the random structure was trimmed until the model converged. Reading time data were log-transformed prior to analysis. The experimental design was not fully balanced, due to the between-items split in our manipulation of orthographic similarity. Whilst the similar/dissimilar split was meaningful in relation to the nonwords (pseudohomophones and spelling controls), it was not meaningful in relation to the two groups of correctly spelled target words (see *Materials and Design*). Including orthographic similarity as a factor in our model with all experimental items included would, therefore, have been erroneous, as 1/3 of the stimuli would have been artificially classed as orthographically similar or dissimilar. For this reason, there were two stages to our analyses. First, we ran an lme model in which each of the nonword conditions was compared to the correctly spelled word condition, including participant group as an interaction. This model allowed us to examine the cost associated with processing nonwords for each of our participant groups. Second, we ran an lme model in which we excluded the correctly spelled words, and only included the nonword conditions, again including participant group as an interaction. This model allowed us to directly examine the effects of phonological cues (pseudohomophones vs. spelling controls) and orthographic cues (orthographically similar vs. dissimilar) on lexical identification during reading in each of our participant groups. Means for each dependent measure, broken down by participant group and experimental condition, are shown in Table 2. The mean number of first pass fixations on the target word/nonword in each sentence is also shown for descriptive purposes; although the formal analyses of this measure did not yield any results that were of additional interest, these descriptive statistics clearly show that participants typically made one or two first pass fixations on the target word/nonword. Analyses of three key dependent measures are reported: first fixation duration (the duration of the initial, first-pass fixation on the target word); refixation duration (the summed duration of all first-pass fixations on the target word minus first fixation duration, typically reflecting second fixation duration); and gaze duration (the sum of all first-pass fixations on the target word, prior to the eyes moving to a different word). These three measures of reading time reflect the time course of lexical identification, from early orthographic encoding when the word is first fixated until the moment when the eyes move to another word in the sentence (thought to indicate that lexical identification has occurred)[5].

Insert Table 2 about here

Model 1. The five experimental conditions were: (1) correctly spelled target words; (2) orthographically similar pseudohomophones; (3) orthographically dissimilar pseudohomophones; (4) orthographically similar spelling controls; and (5) orthographically dissimilar spelling controls. Participant groups were coded as: (1)

teenagers with PCHL; (2) CA controls; and (3) WRA controls. The syntax for this model was: "*lmer(depvar ~ Group*Cond + (1+Cond|Participant) + (1+Group|targetno)"*. Thus, the reading times for teenagers with PCHL on the correctly spelled words provided the intercept for this model. The results of this model, for each of the three dependent measures, are shown in Table 3.

Insert Table 3 about here

Three interesting points can be taken from the results of this model. First, in both first fixation duration and gaze duration, teenagers with PCHL had longer reading times relative to the CA controls, but there was no difference between teenagers with PCHL and the WRA controls. Second, all nonwords received longer reading times than the correctly spelled words. Third, the data indicate that this cost associated with processing nonwords (relatively to correctly spelled words) was very similar across the three participant groups.

Model 2. First, given that the two sets of target words were not matched for length across the two orthographic similarity conditions, we ran an LME model with length as the sole factor (*"lmer(depvar ~ Length + (1+Length |Participant) + (1|targetno)"*. For all three dependent measures, there was no significant effect of word length (all ts < 1). We also ran formal model comparisons to evaluate the influence of word length within our data. These comparisons showed that, for both first fixation duration and gaze duration, including word length did not improve the fit of the model to the data (ps > 0.8). For refixation time, the model that included word length was a marginally better fit to the data than the model without ($p = 0.05$); however, within this model, the main effect of word length was not significant, nor were any of the interactions between word length and our experimental manipulations (all ts < 1.9). In the following analyses, therefore, we report the models without word length. The phonological conditions were coded as: (1) pseudohomophones; and (2) spelling controls. The orthographic conditions were coded as: (1) orthographically similar; and (2) orthographically dissimilar. The participant groups were coded as: (1) CA controls; (2) teenagers with PCHL; and (3) WRA controls. The syntax for this model was: *"lmer(depvar ~ Group*phoncond*orthcond + (1+phoncond*orthcond |Participant) + (1+Group*phoncond|targetno)"*. The *"contr.sdif"* (package MASS) was used to set up the three factors. The results of this model for the three dependent variables can be seen in Table 4.[6]

Insert Table 4 about here

There were two effects that occurred robustly across all three dependent measures. First, the teenagers with PCHL had significantly longer reading times than the CA controls, but were not significantly different to the WRA controls. Second, there was a greater cost associated with processing orthographically dissimilar nonwords relative to orthographically similar nonwords.

Insert Figure 1 about here

The other effects within these analyses showed an extremely interesting pattern of change over time, and will be described in turn (see Figure 1). In first fixation duration, there was no overall difference between pseudohomophones and spelling controls. There were, however, 2-way interactions between phonological condition and both the CA (marginal) and WRA (significant) controls, as well as a marginal 3-way interaction with the CA controls. To explore these effects further, and to make our comparisons of conditions between groups as consistent and comparable as possible, we ran planned contrasts to directly test for a pseudohomophone advantage in each of the three participant groups separately. Specifically, for each group, we compared first fixation durations on pseudohomophones and spelling controls in both the orthographically similar and dissimilar cases. For the CA control group, there was a significant pseudohomophone advantage for the orthographically similar nonwords (b = -0.15, SE = 0.06, t = 2.41), but not for the orthographically dissimilar stimuli (t<1). For both the teenagers with PCHL and the WRA controls, there was no significant pseudohomophone advantage in either the orthographically similar or dissimilar stimuli (all ts<1.96).

In refixation duration (typically the duration of a second, first pass fixation), quite a different pattern emerged. The 2-way interactions between participant group and phonological condition were not significant but, again, there was a 3-way interaction with orthographic similarity for both the CA (significant) and the WRA controls (marginal) relative to the teenagers with PCHL. As in first fixation duration, we ran planned contrasts to directly test for a pseudohomophone advantage in each case. For the CA control group, there was no pseudohomophone advantage during the second fixation on orthographically similar stimuli (t<1) but the pseudohomophone advantage was now significant for the orthographically dissimilar stimuli (b = -0.35, SE = 0.14, t = 2.52). For the teenagers with PCHL, there was still no difference between pseudohomophones and spelling controls within the orthographically dissimilar stimuli (t<1), but there was a significant pseudohomophone advantage for the orthographically similar stimuli (b = -0.39, SE = 0.12, t = 3.17). For the WRA control group, again, reading times were longer on pseudohomophones than spelling controls but this difference was still not significant within either the orthographically similar (b = -0.16, SE = 0.15, t = 1.04) or dissimilar (b = -0.18, SE = 0.14, t = 1.35) stimuli. Thus, across these first two dependent measures, a clear pattern emerged. The older, hearing teenagers showed a pseudohomophone advantage in their very earliest processing of nonwords that were orthographically similar to the correctly spelled base word, and this effect also occurred but was delayed slightly (until the second fixation on the target nonword) for nonwords that were orthographically dissimilar to the correctly spelled base word. For the younger, hearing teenagers, from the very earliest measures of processing, there was a trend for a pseudohomophone advantage but this was not significant in either first fixation duration or refixation duration. For the teenagers with PCHL, the pseudohomophone advantage occurred, but was slightly delayed relative to their age-matched peers, appearing in the second fixation on that target nonword. When the nonword was orthographically dissimilar to the base word, there was no pseudohomophone advantage in these early measures of processing.

In gaze duration, a strikingly clear and simple pattern was observed. There was a pseudohomophone advantage for all participant groups, across both the orthographically similar and dissimilar stimuli. Thus, by the time the readers had processed the nonword letter string sufficiently for them to move their eyes on to another word within the sentence, all readers showed an advantage to having phonological cues that were consistent with the correctly spelled base word.

We noted that our participant samples were not matched for vocabulary, which has been shown to be linked to reading development in both hearing and deaf populations (e.g., Beck, Perfetti & McKeown, 1982; Cain & Oakhill, 2011; Kyle et al., 2010; Kyle & Harris, 2016; Marulis & Neuman, 2010; Perfetti, 2007; Perfetti & Hart, 2002; Scarborough, 2001). In order to examine the influence of this within our data, we ran formal model comparisons which showed that including vocabulary (centred) did not improve the fit of the model to the data for any dependent measure (all *p*s > 0.2).

Finally, within the data from the teenagers with PCHL, we examined the effect of including of two additional variables in our models – individual levels of unaided hearing loss and their reading skill, as measured by the word reading subtest of the WIAT. Both the level of hearing loss and reading skill variables were centred. Formal model comparisons showed that the inclusion of neither of these two additional factors improved the fit of the model to the data for any dependent measure (all *p*s > 0.2). This suggests that, despite quite substantial variations between the teenagers with PCHL in terms of their level of hearing loss and reading skill, they were consistent in their use of phonological and orthographic cues during lexical identification in reading.

Discussion.

First and foremost, these data provide a very clear demonstration that teenagers with PCHL process phonology during lexical identification even when reading silently for meaning, *e.g.*, when the task itself has no explicit requirement for the participant to attend to or process speech sounds. Furthermore, it is likely that such phonological processing was pre-lexical (i.e., that abstract phonological codes for the orthographic stimulus were activated prior to lexical access). The stimuli were nonwords, and so did not have lexical entries; it could not be the case, for example, that the reader had an entry in the mental lexicon for the stimulus, *cherch*, and that stored phonological representations for that stimulus became activated after the lexical entry itself had been accessed (*e.g.*, Lukatela & Turvey, 1994). The processing advantage for a pseudohomophone over a spelling control is likely, therefore, to have been pre-lexical and to have facilitated access to an item in the mental lexicon (e.g., *church*).

The time course of the pseudohomophone advantage varied across participant groups – it emerged in first fixation duration for the older, hearing teenagers (CA controls), in refixation duration for the teenagers with PCHL, and in gaze duration for the younger, hearing teenagers (WRA controls). First, in comparison to the CA controls, this delayed processing of phonology in teenagers with PCHL is consistent with those two groups' relative performance on the two pen-and-paper assessments of phonological processing and phonological decoding. On both of these tasks, teenagers with PCHL had significantly lower scores than their age-matched, hearing peers. It is, therefore, unsurprising that their phonological processing during silent sentence reading is less efficient. It was, however, more unexpected that the teenagers with PCHL demonstrated an earlier pseudohomophone advantage than the WRA controls, given that this latter group obtained significantly higher scores on the two pen-and-paper assessments of phonological processing. With respect to the subtests of the CTOPP, it is worth noting that both are based on the participants' perception of an auditory stimulus, and their generation of an oral response. Even though every effort was made to ensure that the teenagers with PCHL were able to perceive the stimuli (see Footnote ii), it is possible that the perceptual and/or articulatory demands of this task were the cause of the lower performance in teenagers with PCHL relative to their hearing peers, as opposed to their underlying (cognitive) phonological awareness. With respect to the pseudoword decoding test, a likely explanation for these seemingly contradictory patterns in the data is the differing demands of the two tasks. In the eye movement experiment, participants were reading sentences silently for meaning. Access to the lexical entry for the correctly spelled base word should have been facilitated by both phonological and orthographic overlap of the nonword with the base word, and also by the sentence context that was semantically constraining toward the identity of the base word. In contrast, on a pseudoword decoding task, the reader must pronounce aloud a nonword letter string that is presented in isolation and that does not correspond to any existing lexical entry. It is not clear which, if not all, of these task differences might have resulted in relatively weaker performance by the teenagers with PCHL on the pseudoword decoding task – the additional articulatory demand, the lack of a corresponding lexical entry, or the lack of supporting semantic context. What is clear, however, is that during a relatively natural, silent sentence reading task, teenagers with PCHL show evidence of phonological recoding[7], and that within the present sample such processing was not affected by the individual reader's level of hearing loss.

Given the argument that the pseudohomophone advantage observed in Experiment 1 was pre-lexical, and indicative of phonological recoding during silent sentence reading, the subsequent question of interest was whether teenagers with PCHL were sensitive to phonological information in parafoveal preview.

Experiment 2

In Experiment 2, the same target word manipulations were made; here, we used the boundary paradigm (Rayner, 1975) to examine parafoveal pre-processing of phonology and orthography. We made three predictions. First, that all participants would obtain greater preview benefit from orthographically similar previews than orthographically dissimilar previews; sensitivity to orthography in parafoveal preview has previously been reported in skilled adult readers (Binder, Pollatsek & Rayner, 1999; Johnson & Dunne, 2012; McConkie & Zola, 1979; Rayner, McConkie & Zola, 1980), both skilled and less skilled deaf readers (Bélanger *et al.*, 2013), and beginning readers as young as 8-years (Pagan, Blythe, & Liversedge, 2016). Second, that the chronological age-matched control group would show a pseudohomophone advantage from parafoveal pre-processing of phonology; these teenagers could be considered as skilled adult readers, and pre-processing of phonology has previously been demonstrated for similar groups of readers (Pollatsek *et al.*, 1992). Third, that the teenagers with PCHL would not demonstrate a pseudohomophone advantage as those readers were not expected to process phonology within their parafoveal preview. There were two reasons for this final prediction: (1) previous research has demonstrated that pre-processing of phonology is constrained by reading ability, even within adult samples (e.g., Chace *et al.*, 2005); and (2) previous research has indicated that even skilled deaf readers do not extract phonological information during parafoveal pre-processing (Bélanger *et al.*, 2013).

Method.

Participants. As in Experiment 1.

Apparatus. As in Experiment 1.

Materials and Design. As in Experiment 1. Here, the target words/ nonwords were presented using the boundary paradigm (Rayner, 1975). An invisible boundary was programmed immediately after the last letter of the pre-target word. Prior to the eyes crossing that boundary for the first time, the correct words/ pseudohomophones/ spelling controls were presented in the target location. When the reader's eyes first moved across the boundary then a display change was triggered such that the preview stimulus in the target location was replaced on all trials with the correctly spelled word. No target test questions were presented, because participants never directly fixated a misspelled word.

Procedure. As in Experiment 1.

Results. The data were first trimmed using the clean function in DataViewer, with the same procedure and criteria as in Experiment 1. On this basis, 1006 fixations were excluded from the analysis (2.5% of the dataset). We then excluded trials where the display change occurred either too early (during the fixation on the pre-target word) or too late (during the fixation on the target word). Trials in which the display change occurred more than 15ms after fixation onset on the target word were excluded from the analysis (11%). Means for each dependent measure, broken down by participant group and experimental condition, are shown in Table 5.

Insert Table 5 about here

Insert Table 6 about here

Model 1. Two robust effects were observed from the results of Model 1 (see Table 6). Note that these effects come from the analyses of first fixation duration and gaze duration, as there were no significant effects at all in the analysis of refixation duration. This is likely due to the reduced statistical power in that analysis, given that the target word received a refixation on just 16% of trials. First, reading times on the target words were not increased following a preview of an orthographically similar pseudohomophone relative to the identity preview. This suggests that if the preview was both orthographically and phonologically similar to the target word, then pre-processing of that letter string facilitated access of the target word's lexical entry. Similarly, in first fixation duration on the target word, there was also no cost associated with having seen an orthographically similar spelling control preview, but this advantage was not maintained in gaze duration. Second, reading times on the target word were inflated after a parafoveal preview of the other nonword conditions relative to an identity preview – orthographically dissimilar pseudohomophone previews, as well as orthographically similar and dissimilar spelling control previews all increased reading times on the target word.

Insert Table 7 about here

Model 2. Again, we ran an LME model with length as the sole factor (*"lmer(depvar ~ Length + (1+Length |Participant) + (1|targetno)"*. For all three dependent measures, there was no significant effect of word length (all ts < 1.1). We also ran formal model comparisons to evaluate the influence of word length within our data. These comparisons showed that, for all three dependent measures, including word length did not improve the fit of the model to the data (ps > 0.4). In the following analyses, therefore, we report the models without word length.

There was, as predicted, a pseudohomophone advantage that was statistically significant in gaze duration (for all three measures, reading times were longer following a spelling control preview than a pseudohomophone preview; see Table 7). There was also an effect of orthographic similarity – first fixation and gaze durations were significantly shorter following previews that were orthographically similar than those that were orthographically dissimilar to their base word. Of critical interest were the interactions between participant group and these experimental manipulations of phonology and orthography. Strikingly, there were no significant interactions whatsoever, suggesting that all three participant groups exhibited the same pseudohomophone advantage from parafoveal preview, as well as showing shorter reading times from previews that were orthographically similar. This lack of any significant interactions was surprising, and counter to the experimental hypotheses. In particular, it was expected that teenagers with PCHL would not demonstrate a pseudohomophone advantage from parafoveal preview (based on both their reduced reading skill, and previous research that has not found such effects. Additional analyses were conducted, therefore, to further explore the pseudohomophone advantage within the data from teenagers with PCHL.

In each of the following analyses, the dependent variable is gaze duration as this is where the most robust effects were observed in the main analyses. Formal model comparisons were run to determine whether the inclusion of additional variables within the LME models could improve the fit of those models to the data. First, participants' vocabulary score (centred) did not improve the fit of the model to the data ($p > 0.18$). Next, additional analyses were conducted within the sample of teenagers with PCHL. The inclusion of individual participants' level of unaided hearing loss (centred) did not improve the fit of the model to the data ($p = 0.19$). Finally, individual participants' reading skill (as assessed by the word reading subtest of the WIAT-II; centred) did not improve the fit of the model to the data ($p = 0.07$). These additional analyses clearly demonstrate, therefore, that the group of teenagers with PCHL obtained a pseudohomophone advantage in parafoveal preview, and there was no evidence to suggest that this was modulated by either the individual participants' level of hearing loss or their reading skill.

Discussion. The results from Experiment 2 are consistent with those from Experiment 1 (though there were slight differences in the time course of the effects across the two experiments for teenagers with PCHL; see General Discussion). All participant groups showed two clear effects: (1) orthographic similarity, whereby the greater the orthographic overlap between the preview nonword and the correctly spelled target then the shorter the reading times on that target word; and (2) a pseudohomophone advantage, whereby pseudohomophone previews resulted in shorter reading times on the (correctly spelled) target word relative to spelling control previews. There was no evidence whatsoever to suggest that these effects were modulated by participant group. Additional analyses showed that, within the group of teenagers with PCHL, the pseudohomophone advantage was not influenced by the individual's level of hearing loss, nor by their reading skill.

There are two, apparent discrepancies between these data and those from previously published studies. First, it had been previously reported that, despite an overall larger perceptual span than that of their hearing peers, deaf readers do not pre-process phonological information (Bélanger *et al.*, 2013). The most likely explanation for this difference is that two quite different participant samples were recruited. In the Bélanger *et al.* study, the participants were severely to profoundly deaf (hearing loss > 71 dB SPL), and used sign language (ASL) as their primary means of communication. In the present study, the participants had a greater range of level of hearing loss (30 – 126 dB SPL), and all used oral language as their primary means of communication. Here, the analyses of two independent datasets showed no influence of the level of hearing loss whatsoever upon phonological processing during reading, despite the substantial range of hearing loss within the participant sample. The most obvious factor that differentiates between these two studies and that might account for differences in the participants' processing of phonology is, therefore, the primary mode of communication. Presumably, oral language use allowed the participants in the present study to develop relatively well-specified, and abstract, phonological representations that are accessed during silent reading. The source of these phonological representations may be auditory (speech perception), visual (perception of cues from lip reading), or, most likely, a combination of both. What is clear, however, from the present study is that teenagers with PCHL can and do pre-process phonology during silent sentence reading.

Second, previous work has demonstrated that parafoveal pre-processing of phonology is constrained by reading ability to the extent that, even within a sample of adult readers, there is variability in phonological pre-processing (Chace *et al.*, 2005). This, along with the results of the Bélanger *et al.* study, had motivated the prediction of no phonological preview benefit for the teenagers with PCHL. Our analyses showed, however, that reading skill did not modulate parafoveal pre-processing of phonology. It seems clear, therefore, that all readers in the present study were able to obtain a pseudohomophone advantage from parafoveal preview. The most likely reason why we observed phonological preview benefit in the present study where Chace *et al.* did not find such pre-processing in less skilled readers is the particular stimuli used. Here, the target word in each sentence was highly constrained by the semantics of the surrounding sentence context (see *Stimuli pre-screening* for details); specifically, at least 60% of participants in the pre-screening task predicted the target word from the sentence context. In contrast, the target words used by Chace *et al.* were low predictability, such that a maximum of 25% of participants on a pre-screening task predicted the target word from the sentence context. It has previously been demonstrated that phonological processing is facilitated under high constraint conditions (*e.g.*, Rayner *et al.*, 1998) and so it seems likely that the predictable nature of our target words facilitated the readers' parafoveal pre-processing of phonology.

General Discussion

Two experiments were run, comparing teenagers with PCHL to both chronological age-matched and reading age-matched control groups on their foveal processing and parafoveal pre-processing of phonology during lexical identification in silent sentence reading. The results across these two experiments were very clear. First, as would be expected on the basis of the group matching procedures, the eye movement behaviour clearly reflected greater processing difficulty during reading for both teenagers with PCHL and their reading age-matched controls relative to the chronological age-matched controls. Second, despite these overall group differences, the three groups showed highly similar patterns of reading behaviour in response to the two experimental manipulations. Reading times were facilitated when there was a greater degree of orthographic overlap between the nonword and its correctly spelled base word and, critically, they were facilitated for nonwords that shared phonology with the base word.

Across the results from Experiments 1 and 2, there is strong evidence to suggest that the observed pseudohomophone advantage was pre-lexical in nature. First, the stimuli were nonwords (pseudohomophones and spelling controls) that do not have lexical entries; it could not have been the case, therefore, the stimulus' phonological representation was being activated post-lexically on the basis of the orthographic input (*e.g.*, Lukatela & Turvey, 1994). Second, the pseudohomophone advantage was observed during both direct fixation on the nonwords, and during fixations on correctly spelled words following a nonword preview. Given that over 80% of target words received a first pass fixation (e.g., were not skipped) then there is no reason to think that readers were fully identifying those target words on the basis of the preview letter string. Again, this suggests that the pseudohomophone advantage observed in preview benefit was pre-lexical.

These experiments also allowed for a more general investigation of the nature of reading difficulties associated with hearing loss through the recruitment of both chronological age-matched and reading age-matched control groups. If the reading behaviour of teenagers with PCHL were clearly different to that of both control groups then this would have indicated some atypical cognitive processing associated with hearing loss, beyond a simple developmental delay. In fact, there were no differences in any aspect of the data between the teenagers with PCHL and their reading age-matched controls (who were, on average, 43 months younger). These global reading behaviours do not, therefore, provide any evidence for atypical cognitive processing during reading. Furthermore, the data from Experiment 2 did not show any specific differences in phonological processing in parafoveal preview between the teenagers with PCHL and either of the two control groups. In Experiment 1, however, there was one aspect of the data that varied between participant groups – for manipulated stimuli that were directly fixated, the pseudohomophone advantage was delayed in teenagers with PCHL relative to chronological age-matched controls. The pen-and-paper assessments of all participants showed very clearly that the teenagers with PCHL had impaired phonological awareness and decoding skills relative to both control groups. In this context it is, perhaps, unsurprising that processing of phonology might be less efficient during lexical identification for the teenagers with PCHL. Why, then, was a similar delay in processing of phonology not observed in Experiment 2? Previous work has shown that deaf readers have a larger perceptual span, and allocate more attention to the parafovea, than their hearing peers during reading. This may be the reason, therefore, why the teenagers with PCHL in the present study showed equally effective phonological processing during parafoveal preview as their heading peers (Experiment 2), but it was only when the nonwords were directly fixated that phonological processing was delayed (Experiment 1).

What is clear from the broader literature on literacy skills in deaf children is that their reading does not reflect a simple developmental delay; instead, the gap in reading attainment between deaf children and their hearing peers seems to widen over time (*e.g.*, Pimperton *et al.*, 2016). The present study suggests that phonological processing during lexical identification may be one part of these reading difficulties, but it is unlikely to be the primary cause. Although phonological processing was found to be slightly delayed during identification of fixated words, the teenagers with PCHL obtained the same pseudohomophone advantage as their hearing peers by the time that they moved their eyes to a different word within the sentence. Although interesting, and worthy of further investigation in the future to better understand this delay, it is hard to see how this difference could possibly underlie the substantial reading difficulties that are common in deaf/ hard of hearing individuals. It is also important to note that the eye movement experiments allowed for the investigation of phonological recoding during lexical identification during silent sentence reading, and found a relatively minor cost in the teenagers with PCHL. This stands in stark contrast to the pen-and-paper assessments of both phonological awareness and decoding skills, which indicated more substantial difficulties in the teenagers with PCHL relative to their hearing peers. The nature of the task can, clearly, have a tremendous influence on the observed patterns of behaviour, and it is vital that conclusions concerning cognitive processing during reading are drawn of the basis of data from tasks that approximate natural reading as closely as possible.

Three conclusions can be drawn from these experiments. First, in the case of teenagers with PCHL who communicate using oral language, the combination of reduced/ degraded auditory cues and visual cues from lip-reading during speech perception are sufficient to allow pre-lexical phonological recoding during silent sentence reading. Second, during processing of directly fixated stimuli, phonological processing is slightly delayed in teenagers with PCHL relative to their hearing peers. Third, the well-documented reading difficulties associated with hearing loss are likely to be primarily attributable to other aspects of reading, and not to such a minor impairment in phonological processing.

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[1] Note that the participants' raw scores on the word reading test were used to match the PCHL group and the WRA control group. Standardized scores represent an individual's ability in relation to what would typically be expected for someone of that age. Unsurprisingly, given the well-established reading difficulties associated with deafness, standardized reading scores for the PCHL sample were quite low and use of these scores to identify the control group would have resulted in a group of normally hearing individuals who also had atypically low reading abilities relative to their age and educational opportunity. Whilst such comparisons would clearly be of interest, the aim here was to make a comparison with a group of teenagers with both normal hearing and typical literacy development.

[2] For the Blending Words subtest, the stimuli are usually presented using the audio recording provided on a CD with the test kit; however, many of the participants with PCHL were unable to hear this recording sufficiently well even to complete the practise items. This was, perhaps, unsurprising as most of those participants reported that they relied on lip-reading to support their day-to-day speech perception. Given that this test was intended to assess phonological processing skills, not hearing level, we gave all participants with PCHL the option of having the Blending Words stimuli read out loud by the experimenter if they indicated during the practise items that they were unable to hear the audio recording (11/23 participants in the PCHL group completed this test with the experimenter; the remainder completed this test with the CD; all hearing participants used the CD). There was no significant difference in CTOPP score between those who used the CD, and those who heard/saw the experimenter reading the items aloud (t_1 (21) = 0.51, p = 0.62).

[3] Participants are typically given 40 minutes to complete the SPM+, and the standardized scores are based on normative data from those testing conditions. Due to time limits for individual test sessions in the present study, each participant was allowed just 20 minutes to complete the SPM+ test; the absolute values will, therefore, under-estimate the participants' standardized IQ scores relative to the general population. For group-matching purposes, however, this was not a problem as all participants completed the SPM+ under the same conditions.

[4] First, fixations shorter than 80 ms that were within 0.5 deg of another, longer fixation were merged with that longer fixation. Second, fixations shorter than 40 ms that were within 1.25 deg of another, longer fixation were merged with that longer fixation. Third, for any words that still received at least three fixations shorter than 140 ms but none that were longer, those three short fixations were merged. Fourth, and finally, any remaining fixations shorter than 80 ms or longer than 1200 ms were deleted.

[5] For an overview of different reading time measures, and the cognitive processes those measures are thought to reflect, see Juhasz and Pollatsek (2011).

[6] For each dependent measure, we also ran an omnibus test using the anova function within the car package, to examine the main effects of our experimental manipulations and their interactions. For the sake of parsimony, we do not report theses results in full as the pattern of effects was consistent with the results of the LME models. Notably, there were significant/ marginal interactions between participant group and the phonological manipulation for first fixation duration and refixation duration (ps $\leq$ 0.07), but not for gaze duration (ps > 0.6) in Experiment 1. In contrast, for Experiment 2, there were no significant interactions between participant group and the phonological manipulation for any dependent measure (ps > 0.2).

[7] With a sample size of 23 per participant group, these analyses may have had low statistical power for detecting small effects. The non-significant interaction between participant group and the pseudohomophone advantage may, therefore, be treated with caution. It is possible, in principle, that with a sample of over 170 participants with PCHL, this interaction term may become statistically significant. It would, however, be impracticable to recruit a sample of that size. A birth cohort of 157,000 infants born in the UK between 1993 and 1996 resulted in a sample of 120 infants with PCHL (Kennedy *et al.*, 1998). Seventy six of those 120 children were willing to take part in a follow up study as teenagers (Pimperton *et al.*, 2015); we recruited every participant within that sample of 76 who was willing to take part in the currently reported study.

Table 1.

		N	Mean	STDev	t	df	p
Test age	PCHL	23	222	14			
(months)	CA controls	23	216	13	1.45	44	0.156
	WRA controls	23	179	5	13.21	44	0.000
Word reading	PCHL	23	115	8			
(raw)	CA controls	23	125	3	5.09	44	0.000
	WRA controls	23	119	5	1.69	44	0.098
Word reading	PCHL	23	90	15			
(standardized)	CA controls	23	107	5	5.02	44	0.000
	WRA controls	23	99	9	2.31	44	0.026
Pseudoword decoding	PCHL	23	37	13			
(raw)	CA controls	23	49	3	4.38	44	0.000
	WRA controls	23	45	7	2.51	44	0.016
Pseudoword decoding	PCHL	23	84	16			
(standardized)	CA controls	23	106	6	6.17	44	0.000
	WRA controls	23	97	11	3.29	44	0.002
Phonological processing	PCHL	23	19	7			
(sum of raw scores)	CA controls	23	31	6	6.15	44	0.000
	WRA controls	23	28	7	4.44	44	0.000
Phonological processing	PCHL	23	10	5			
(sum of standardized scores)	CA controls	23	18	4	6.47	44	0.000
	WRA controls	23	18	5	5.34	44	0.000
Receptive vocabulary	PCHL	23	144	15			
(raw)	CA controls	23	158	3	4.55	44	0.000
	WRA controls	23	150	6	2.00	44	0.051
Receptive vocabulary	PCHL	21[a]	92	13			
(standardized)	CA controls	23	105	6	4.37	42	0.000
	WRA controls	23	100	14	2.06	42	0.046
Nonverbal IQ	PCHL	23	33	6			
(raw)	CA controls	23	34	5	0.89	44	0.379
	WRA controls	23	32	6	0.36	44	0.723
Nonverbal IQ	PCHL	23	86	16			
(standardized)*	CA controls	23	90	15	0.87	44	0.391
	WRA controls	23	93	17	1.46	44	0.151

*Data from the pen-and-paper assessments of reading, vocabulary, phonological processing skills, and nonverbal IQ for the three participant groups. The three right-hand columns give the results of independent samples t-tests comparing each of the two control groups to the PCHL group for each dependent measure. *The IQ test was administered as a short (20 minute) version due to time limits within testing sessions (it is typically completed with a 40 minute time limit); hence, the standardized scores would not be expected to fall within a distribution centred around 100. [a]Two participants achieved an extremely low raw score on this task, such that it was not possible to convert it into a standardized score relative to their age. Thus, the means and statistical comparisons here are likely to be under-estimating a group difference in vocabulary.*

Table 2.

		First fixation duration (ms)	Refixation duration (ms)	Gaze duration (ms)	Number of first pass fixations
CA controls	Correctly spelled	208 (82)	215 (205)	244 (137)	1.16 (0.42)
	Orthographically similar pseudowords	213 (83)	251 (114)	295 (153)	1.46 (0.61)
	Orthographically dissimilar pseudowords	262 (115)	211 (99)	324 (154)	1.43 (0.55)
	Orthographically similar spelling controls	254 (111)	245 (126)	340 (158)	1.67 (0.53)
	Orthographically dissimilar spelling controls	240 (78)	357 (309)	376 (281)	1.58 (0.84)
PCHL teens	Correctly spelled	239 (81)	212 (81)	268 (110)	1.16 (0.43)
	Orthographically similar pseudowords	285 (127)	262 (137)	395 (195)	1.46 (0.58)
	Orthographically dissimilar pseudowords	339 (231)	418 (248)	471 (307)	1.43 (0.75)
	Orthographically similar spelling controls	255 (11)	373 (151)	437 (240)	1.67 (0.82)
	Orthographically dissimilar spelling controls	310 (174)	393 (188)	486 (262)	1.58 (0.74)
WRA controls	Correctly spelled	222 (68)	234 (165)	244 (109)	1.11 (0.35)
	Orthographically similar pseudowords	257 (134)	351 (249)	344 (219)	1.31 (0.61)
	Orthographically dissimilar pseudowords	286 (153)	333 (170)	384 (221)	1.38 (0.65)
	Orthographically similar spelling controls	270 (104)	378 (188)	386 (224)	1.44 (0.75)
	Orthographically dissimilar spelling controls	318 (174)	409 (238)	468 (305)	1.46 (0.70)

Mean (standard deviation) for each dependent measure from Experiment 1, broken down by participant group and experimental condition. The mean number of first pass fixations per target word/nonword is also reported here for descriptive purposes.

Table 3.

		b	SE	t
FFDur	Intercept (PCHL, correctly spelled words)	5.42	0.04	138.73
	CA controls	**-0.16**	**0.05**	**-3.33**
	WRA controls	-0.07	0.05	-1.40
	Orthographically similar pseudohomophones	**0.15**	**0.05**	**2.72**
	Orthographically dissimilar pseudohomophones	**0.22**	**0.07**	**3.34**
	Orthographically similar spelling controls	0.05	0.06	0.93
	Orthographically dissimilar spelling controls	**0.19**	**0.06**	**3.00**
	CA, orthographically similar pseudohomophones	-0.11	0.07	-1.51
	WRA, orthographically similar pseudohomophones	-0.03	0.07	-0.37
	CA, orthographically dissimilar pseudohomophones	-0.01	0.09	-0.08
	WRA, orthographically dissimilar pseudohomophones	-0.02	0.09	-0.27
	CA, orthographically similar spelling controls	0.13	0.08	1.68
	WRA, orthographically similar spelling controls	0.13	0.08	1.72
	CA, orthographically dissimilar spelling controls	-0.02	0.09	-0.28
	WRA, orthographically dissimilar spelling controls	0.09	0.09	1.02
RefixDur	Intercept (PCHL, correctly spelled words)	5.33	0.12	43.26
	CA controls	-0.12	0.17	-0.74
	WRA controls	-0.09	0.18	-0.47
	Orthographically similar pseudohomophones	0.11	0.15	0.73
	Orthographically dissimilar pseudohomophones	**0.54**	**0.16**	**3.46**
	Orthographically similar spelling controls	**0.51**	**0.14**	**3.72**
	Orthographically dissimilar spelling controls	**0.53**	**0.16**	**3.38**
	CA, orthographically similar pseudohomophones	0.09	0.21	0.41
	WRA, orthographically similar pseudohomophones	0.36	0.23	1.57
	CA, orthographically dissimilar pseudohomophones	**-0.49**	**0.22**	**-2.28**
	WRA, orthographically dissimilar pseudohomophones	-0.09	0.23	-0.40
	CA, orthographically similar spelling controls	-0.33	0.20	-1.67
	WRA, orthographically similar spelling controls	0.07	0.21	0.31
	CA, orthographically dissimilar spelling controls	-0.06	0.22	-0.28
	WRA, orthographically dissimilar spelling controls	0.08	0.23	0.34
Gaze	Intercept (PCHL, correctly spelled words)	5.51	0.05	101.53
	CA controls	-0.14	0.08	-1.86
	WRA controls	-0.10	0.07	-1.37
	Orthographically similar pseudohomophones	**0.33**	**0.07**	**4.90**
	Orthographically dissimilar pseudohomophones	**0.43**	**0.07**	**6.47**
	Orthographically similar spelling controls	**0.40**	**0.07**	**6.03**
	Orthographically dissimilar spelling controls	**0.49**	**0.07**	**7.28**
	CA, orthographically similar pseudohomophones	-0.14	0.10	-1.46
	WRA, orthographically similar pseudohomophones	-0.04	0.09	-0.39
	CA, orthographically dissimilar pseudohomophones	-0.15	0.09	-1.59
	WRA, orthographically dissimilar pseudohomophones	-0.05	0.09	-0.56
	CA, orthographically similar spelling controls	-0.05	0.09	-0.53
	WRA, orthographically similar spelling controls	0.02	0.09	0.20
	CA, orthographically dissimilar spelling controls	-0.10	0.09	-1.11
	WRA, orthographically dissimilar spelling controls	0.03	0.09	0.34

Experiment 1, output from Model 1. Note that these reading time data were log transformed prior to analysis, thus the model estimates cannot be directly interpreted (see Table 2 for means and standard deviations). Significant effects are marked in bold.

Table 4.

	First fixation duration			Refixation duration			Gaze duration		
	b	SE	t	b	SE	t	b	SE	t
Intercept (grand mean)	5.51	0.03	213.82	5.65	0.03	163.70	5.80	0.04	157.47
Group (PCHL vs. CA)	**0.16**	**0.05**	**3.00**	**0.32**	**0.07**	**4.75**	**0.25**	**0.08**	**3.38**
Group (PCHL vs. WRA)	-0.02	0.06	0.36	0.02	0.07	0.35	-0.11	0.07	1.48
PhonCond	0.02	0.03	0.69	**0.18**	**0.08**	**2.27**	**0.10**	**0.05**	**2.07**
OrthCond	**0.09**	**0.04**	**2.16**	0.12	0.07	1.79	0.10	0.06	1.74
Group x PhonCond (PCHL vs. CA)	-0.11	0.07	1.67	0.04	0.14	0.28	-0.08	0.09	0.81
Group x PhonCond (PCHL vs. WRA)	**0.14**	**0.07**	**2.05**	-0.06	0.15	0.40	0.08	0.09	0.86
Group x OrthCond (PCHL vs. CA)	0.03	0.07	0.40	0.19	0.13	1.50	0.02	0.09	0.26
Group x OrthCond (PCHL vs. WRA)	-0.01	0.08	0.15	-0.24	0.13	1.81	0.02	0.09	0.24
PhonCond x OrthCond	-0.03	0.06	0.55	-0.01	0.15	0.05	-0.01	0.10	0.13
Group x PhonCond x OrthCond (PCHL vs. CA)	0.27	0.14	1.85	**-0.88**	**0.26**	**3.46**	0.06	0.18	0.35
Group x PhonCond x OrthCond (PCHL vs. WRA)	-0.06	0.14	0.42	0.49	0.26	1.88	0.00	0.17	0.03

Experiment 1, output from Model 2. Note that these reading time data were log transformed prior to analysis, thus the model estimates cannot be directly interpreted (see Table 2 for means and standard deviations). Significant effects are marked in bold.

Table 5.

		First fixation duration (ms)	Refixation duration (ms)	Gaze duration (ms)	Number of first pass fixations	Skipping probability
CA controls	Correctly spelled	209 (82)	191 (106)	238 (114)	1.15 (0.36)	0.21
	Orthographically similar pseudowords	213 (62)	154 (68)	245 (83)	1.20 (0.41)	0.14
	Orthographically dissimilar pseudowords	224 (58)	153 (33)	254 (76)	1.19 (0.40)	0.12
	Orthographically similar spelling controls	220 (64)	186 (72)	265 (93)	1.25 (0.47)	0.13
	Orthographically dissimilar spelling controls	235 (56)	182 (119)	261 (80)	1.14 (0.35)	0.11
PCHL teens	Correctly spelled	240 (95)	220 (79)	264 (124)	1.12 (0.34)	0.18
	Orthographically similar pseudowords	246 (115)	179 (63)	266 (137)	1.11 (0.32)	0.16
	Orthographically dissimilar pseudowords	267 (96)	221 (100)	330 (139)	1.28 (0.45)	0.13
	Orthographically similar spelling controls	244 (73)	214 (80)	287 (118)	1.22 (0.45)	0.20
	Orthographically dissimilar spelling controls	274 (106)	227 (151)	306 (124)	1.14 (0.35)	0.17
WRA controls	Correctly spelled	224 (67)	180 (74)	244 (91)	1.11 (0.32)	0.16
	Orthographically similar pseudowords	226 (78)	222 (152)	247 (103)	1.11 (0.36)	0.15
	Orthographically dissimilar pseudowords	268 (91)	227 (137)	303 (130)	1.15 (0.36)	0.10
	Orthographically similar spelling controls	249 (77)	192 (61)	275 (112)	1.14 (0.35)	0.09
	Orthographically dissimilar spelling controls	259 (82)	239 (227)	324 (155)	1.27 (0.45)	0.14

Mean (standard deviation) for each dependent measure in Experiment 2, broken down by participant group and experimental condition. The mean number of first pass fixations per target word/nonword, and skipping probability, are also reported here for descriptive purposes.

Table 6.

		b	SE	t
FFDur	Intercept (PCHL, correctly spelled words)	5.41	0.04	139.00
	CA controls	**-0.13**	**0.05**	**2.46**
	WRA controls	-0.04	0.05	0.71
	Orthographically similar pseudohomophones	0.04	0.05	0.74
	Orthographically dissimilar pseudohomophones	**0.12**	**0.05**	**2.31**
	Orthographically similar spelling controls	0.05	0.05	1.06
	Orthographically dissimilar spelling controls	**0.15**	**0.05**	**3.15**
	CA, orthographically similar pseudohomophones	0.01	0.07	0.10
	WRA, orthographically similar pseudohomophones	-0.04	0.07	0.50
	CA, orthographically dissimilar pseudohomophones	-0.01	0.07	0.21
	WRA, orthographically dissimilar pseudohomophones	0.04	0.07	0.59
	CA, orthographically similar spelling controls	0.02	0.07	0.23
	WRA, orthographically similar spelling controls	0.05	0.07	0.70
	CA, orthographically dissimilar spelling controls	0.00	0.06	0.05
	WRA, orthographically dissimilar spelling controls	-0.02	0.06	0.25
RefixDur	Intercept (PCHL, correctly spelled words)	5.36	0.12	46.39
	CA controls	-0.28	0.15	1.84
	WRA controls	-0.23	0.15	1.50
	Orthographically similar pseudohomophones	-0.28	0.19	1.52
	Orthographically dissimilar pseudohomophones	-0.09	0.14	0.67
	Orthographically similar spelling controls	-0.13	0.16	0.83
	Orthographically dissimilar spelling controls	-0.09	0.17	0.52
	CA, orthographically similar pseudohomophones	0.13	0.23	0.58
	WRA, orthographically similar pseudohomophones	0.43	0.26	1.67
	CA, orthographically dissimilar pseudohomophones	-0.04	0.20	0.20
	WRA, orthographically dissimilar pseudohomophones	0.24	0.21	1.15
	CA, orthographically similar spelling controls	0.18	0.21	0.88
	WRA, orthographically similar spelling controls	0.21	0.22	0.95
	CA, orthographically dissimilar spelling controls	0.11	0.23	0.49
	WRA, orthographically dissimilar spelling controls	0.19	0.21	0.88
Gaze	Intercept (PCHL, correctly spelled words)	5.48	0.05	117.10
	CA controls	-0.10	0.06	1.71
	WRA controls	-0.05	0.06	0.75
	Orthographically similar pseudohomophones	0.04	0.06	0.70
	Orthographically dissimilar pseudohomophones	**0.22**	**0.06**	**3.85**
	Orthographically similar spelling controls	**0.12**	**0.06**	**1.98**
	Orthographically dissimilar spelling controls	**0.18**	**0.06**	**3.26**
	CA, orthographically similar pseudohomophones	0.04	0.08	0.45
	WRA, orthographically similar pseudohomophones	-0.02	0.08	0.26
	CA, orthographically dissimilar pseudohomophones	-0.11	0.08	1.39
	WRA, orthographically dissimilar pseudohomophones	-0.04	0.08	0.52
	CA, orthographically similar spelling controls	0.02	0.08	0.24
	WRA, orthographically similar spelling controls	0.01	0.08	0.15
	CA, orthographically dissimilar spelling controls	-0.04	0.08	0.48
	WRA, orthographically dissimilar spelling controls	0.07	0.08	0.96

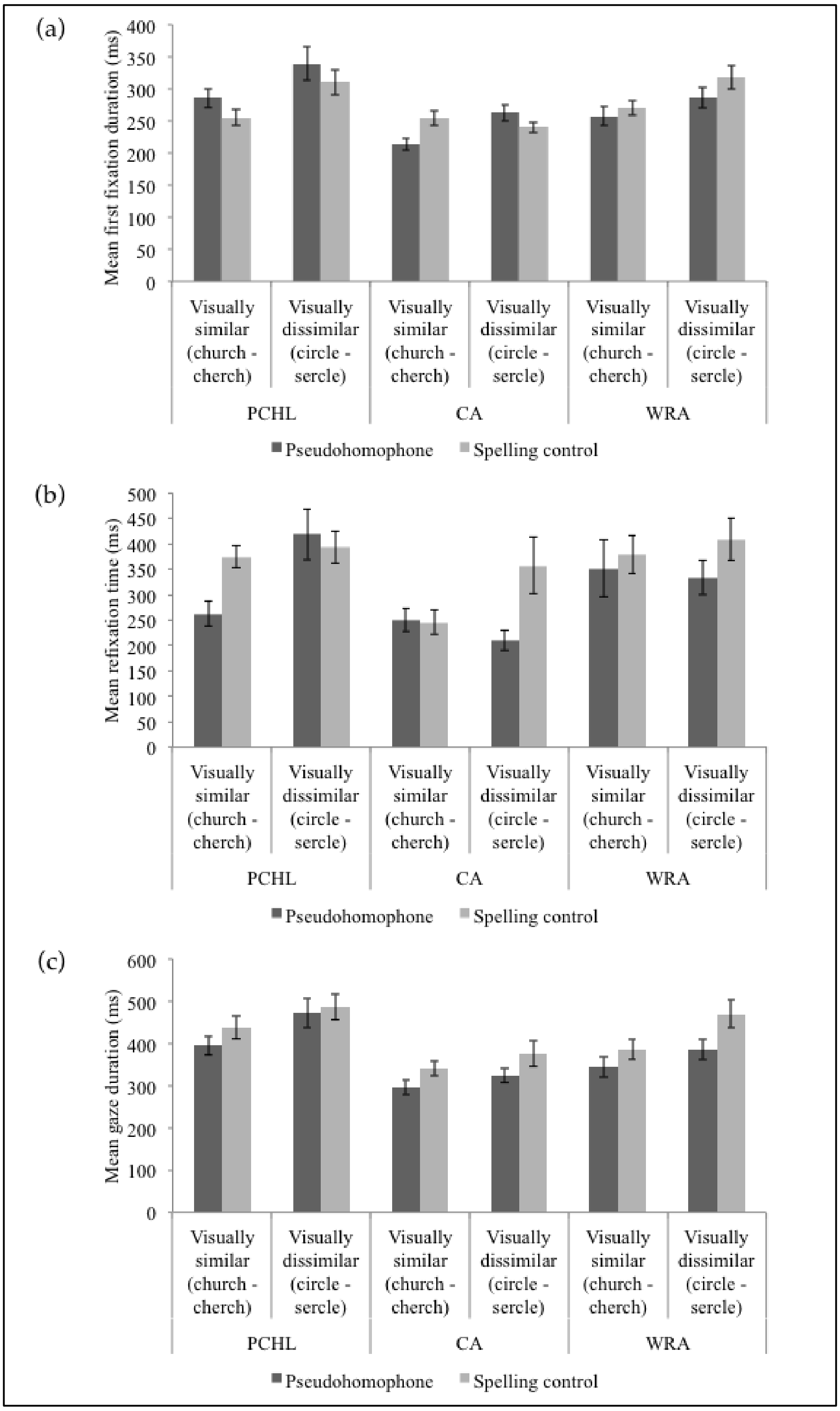
Experiment 2, output from Model 1. Note that these reading time data were log transformed prior to analysis, thus the model estimates cannot be directly interpreted (see Table 5 for means and standard deviations). Significant effects are marked in bold.

Table 7.

	First fixation duration			Refixation duration			Gaze duration		
	b	SE	t	b	SE	t	b	SE	t
Intercept (grand mean)	5.45	0.02	308.26	5.15	0.05	99.59	5.56	0.03	197.07
Group (PCHL vs. CA)	**0.13**	**0.04**	**3.21**	**0.21**	**0.10**	**2.08**	**0.13**	**0.05**	**2.49**
Group (PCHL vs. WRA)	-0.03	0.04	0.72	0.03	0.10	0.31	-0.04	0.05	0.84
PhonCond	0.03	0.03	1.31	0.04	0.07	0.61	**0.05**	**0.03**	**1.97**
VisCond	**-0.09**	**0.03**	**3.54**	-0.04	0.09	0.48	**-0.11**	**0.05**	**2.50**
Group x PhonCond (PCHL vs. CA)	-0.01	0.05	0.27	-0.05	0.16	0.30	-0.03	0.06	0.50
Group x PhonCond (PCHL vs. WRA)	0.02	0.05	0.29	-0.18	0.17	1.10	0.07	0.07	1.05
Group x VisCond (PCHL vs. CA)	-0.02	0.05	0.44	-0.11	0.16	0.70	-0.09	0.06	1.57
Group x VisCond (PCHL vs. WRA)	-0.01	0.05	0.14	0.12	0.17	0.73	-0.04	0.06	0.66
PhonCond x VisCond	0.03	0.05	0.67	0.07	0.13	0.52	0.07	0.05	1.31
Group x PhonCond x VisCond (PCHL vs. CA)	0.01	0.10	0.15	0.10	0.31	0.31	0.09	0.12	0.75
Group x PhonCond x VisCond (PCHL vs. WRA)	0.13	0.10	1.36	-0.15	0.32	0.47	-0.09	0.13	0.69

Experiment 2, output from Model 2. Note that these reading time data were log transformed prior to analysis, thus the model estimates cannot be directly interpreted (see Table 5 for means and standard deviations). Significant effects are marked in bold.

Figure 1. Mean first fixation duration (panel a), refixation time (panel b), and gaze duration (panel c), on pseudohomophones and spelling controls, for each of the three participant groups.



Appendix

Experiment 1, orthographically similar
When mum cooks pasta I like grated cheese/cheeze/cheene on top of it.
The vicar prayed in the old church/cherch/charch every day even though it was cold.
Because he is in charge, we followed our scout leader/leeder/leuder up the hill.
A baby dog is called a puppy/puppi/puppa and is very small and cute.
The knight used a sword and shield/sheeld/sheuld to fight in the battle.
Jane wore tights under her mini skirt/skert/skart at the party.
Sunshine is warm in the spring and hot in the summer/summur/summor normally.
The door was locked so I climbed in through the window/windoe/windou last night.
There are twelve months in every year/yeer/yeor and these make four seasons.
Rudolph the reindeer has a red nose/noze/nove, unlike the others.
My brother is a soldier in the army/armi/armo but he came home for Christmas.
You can get rid of mistakes in pencil with the rubber/rubbur/rubbir on the end.

Experiment 1, orthographically dissimilar
Winnie the Pooh loves to eat honey/hunni/henma straight out of jars.
Lisa likes to drink fresh orange juice/jooce/jeece with her breakfast every day.
We paid the man a lot of money/munni/menro to clean all the windows.
When the lady marries the king, she will become the queen/kween/treen tomorrow.
I had an ice cream yesterday and poured chocolate sauce/sorce/sonce over it.
Gareth threw the rugby ball/borl/bewl to his friend who caught it.
Alex went outside to make a phone call/kawl/tarl because it was noisy inside.
The bus driver beeped his horn/hawn/hemn to let us know he was there.
I tried to draw a perfect round circle/sercle/norcle, but it was hard.
We visited a pottery and made mugs out of wet clay/kley/bloy this morning.
If you eat an apple, most people throw the core/korr/borz away afterwards.
At the building site they lifted the bricks with a tall crane/krain/drauv today.

Experiment 2, orthographically similar
Cheddar is my favourite kind of cheese/cheeze/cheene to have for lunch.
My sister got married in an old stone church/cherch/charch in Scotland.
We were taught to tie knots by our scout leader/leeder/leuder tonight.
We got our dog when she was a tiny puppy/puppi/puppa a long time ago.
The knight carried his sword and shield/sheeld/sheuld when we went into battle.
Lisa wore trousers instead of her skirt/skert/skart when she went out.
We have a school holiday when it is hot in the summer/summur/summor which I love.
The curtains were closed behind the broken window/windoe/windou last night.
I am just 13 now so I will become 14 next year/yeer/yeor on my birthday.
The friendly dog sniffed me with his wet nose/noze/nove and it tickled.
Dad fought in a war because he was a soldier in the army/armi/armo years ago.
On the end of my new pencil is a pink rubber/rubbur/rubbir which I use a lot.

Experiment 2, orthographically dissimilar
Cows make milk and bees make honey/hunni/henma which tastes nice.
It is healthier to drink fruit juice/jooce/jeece than fizzy pop.

I decided to buy some sweets with my pocket money/munni/menro this week.
People cheered for the king and queen/kween/treen as they waved from the window.
The chips were nice when I squeezed lots of brown sauce/sorce/sonce over them.
My uncle hit the golf ball/borl/bewl hard and it went right over the hill.
I used my mobile phone to make a quick call/kawl/tarl to my friend.
My dad sits in the car and beeps the horn/hawn/hemn when he is ready to go.
I drew around a plate to make a perfect circle/sercle/norcle for my picture.
To make a pot, the artist used some wet clay/kley/bloy in his workshop.
Apple pips are in the middle bit, called the core/korr/borz, that you don't eat.
The men lifted the car onto the lorry with a big crane/krain/drauv today.