Phonological Coding during Sentence Reading in Chinese Deaf Readers: An Eye-Tracking Study

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Phonological coding plays an important role in reading for hearing students. Experimental findings regarding phonological coding in deaf readers are controversial, and whether deaf readers are able to use phonological coding remains unclear. In the current study we examined whether Chinese deaf students could use phonological coding during sentence reading. Deaf middle school students, chronological age-matched hearing students, and reading ability-matched hearing students had their eye movements recorded as they read sentences containing correctly spelled characters, homophones, or unrelated characters. Both hearing groups had shorter total reading times on homophones than they did on unrelated characters. In contrast, no significant difference was found between homophones and unrelated characters for the deaf students. However, when the deaf group was divided into more-skilled and less-skilled readers according to their scores on reading fluency, the homophone advantage noted for the hearing controls was also observed for the more-skilled deaf students.

Keywords: deaf readers; sentence reading; phonological coding; eye movements

Word count: 5974

Introduction

Previous studies have found that many deaf individuals or hearing-impaired students experience difficulty in learning to read, and the literacy development of average deaf readers is delayed compared with their hearing peers (Kyle & Cain, 2015; Wauters, van Bon, & Tellings, 2006). It is a significant achievement for deaf students to be able to read at an age-appropriate level, but the majority fail to attain a level of literacy that enables them to cope with the daily demands of modern society (Harris & Moreno, 2004). Investigating the cause of the reading difficulty in the deaf is thus very important. Moreover, attaining understanding of the nature of reading in the deaf would be expected to contribute to theoretical models of reading (e.g. Mayberry, del Giudice, & Lieberman, 2011).

Since the main difference between deaf and hearing students is the lack of auditory experience, one plausible hypothesis for reading difficulties in deaf readers is that they fail to develop a fully specified phonological representation of words (Bélanger, Baum, & Mayberry, 2012). In the present study we examined whether Chinese deaf readers are able to use phonological coding during reading.

For hearing readers, phonological coding is critical for high reading achievement (Perfetti & Sandak, 2000). According to cognitive models of reading (Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; Ziegler & Goswami, 2005), the route by which readers access semantics may either be directly from orthography, or indirectly via phonological mediation during reading. Regardless of which route is used for semantic access, a number of studies have supported that phonological coding plays an important role in the reading of hearing readers, even in logographic scripts like Chinese (Grainger & Ferrand, 1994; Lee, Rayner, & Pollatsek,1999; Lukatela, Frost, & Turvey, 1998; Tan & Perfetti, 1998). A four-year longitudinal study examined the relationship between Chinese children's phonological skills and their success in reading (Ho & Bryant, 1997). The results showed that prereading phonological skills strongly predicted children's reading performance two to three years later.

However, the experimental findings of how phonological coding occurs among deaf students have been controversial (Mayberry et al., 2011). One view suggests that deaf readers could activate phonological coding during reading in the same way as hearing readers (Musselman, 2000; Transler & Reitsma, 2005), and the difficulty of reading in deaf readers might be due to delayed reading development (Paul & Lee, 2010). An opposing view (to the delayed reading development view) is that deaf readers have little reliance on phonological coding (Fariña, Duñabeitia, & Carreiras, 2017; McQuarrie & Parrila, 2009; Perea, Marcet, & Vergara-Martinez, 2016), and instead prefer to use different qualitative processes during reading (nonauditory channels, such as visual lip reading, sign language; see Bélanger et al., 2012).

However, much of this research has used isolated word recognition tasks (single/double-character word recognition task) or phonology judgment tasks. For example, Friesen and Joanisse (2012) reported a study that required hearing and deaf adults to perform lexical decisions on homophones and control words in the context of either pseudoword foils (e.g., CLANE) or pseudohomophone foils (e.g., BRANE). Deaf readers responded more slowly to homophones than to control words in the pseudohomophone foil context, but not in the pseudoword foil context, whereas hearing readers responded more slowly to homophones than to control words in both non-word contexts. This finding suggests that deaf readers had activated phonological representations, but these activations were either different from or not as detailed as the representations activated in the hearing group. However, Fariña, Duñabeitia, and Carreiras (2017) used a lexical decision task and found that hearing adults made a higher percentage of errors when rejecting pseudohomophones compared to control nonwords, whereas error rates for deaf adults were similar between pseudohomophones and control nonwords, suggesting that the deaf adults did not activate phonological coding in this study.

Importantly, the studies reported above that have employed isolated word recognition tasks may not reflect on-line cognitive processing during natural reading, and as such any investigation of the roles of phonological skills in single word reading cannot provide a full account of phonological processing in sentence or passage reading. Little research to date has directly examined the phonological coding of deaf readers in natural sentence reading (only three studies have investigated this in alphabetic languages). Hanson, Goodell, and Perfetti (1991) used tongue twisters to test whether deaf readers activated phonological coding in sentence reading. They found that both deaf and hearing college students made more errors in their acceptability judgments on tongue-twisters than they did on control sentences which indicated that deaf readers can use phonological coding during reading.

Recently eye movement methodology has been adopted to investigate whether deaf readers activate phonological coding during natural and silent sentence reading as they read. The eye movement data are very informative as they allow us to understand whether there are on-line processing differences between the deaf and hearing readers during natural sentence reading. For example, Bélanger, Mayberry, and Rayner (2013) used the boundary paradigm to explore adult deaf readers' processing of phonological coding in parafoveal vision (the word next to the currently fixated word) during sentence reading. They found no evidence for a parafoveal phonological preview benefit in both skilled and less-skilled deaf readers, but hearing readers showed a phonological preview benefit. In contrast, Blythe, Dickins, Kennedy, and Liversedge (2018) adopted the same boundary paradigm and observed phonological coding from parafoveal vision in deaf teenagers. In another study, Blythe et al. (2018) used the error disruption paradigm to examine phonological coding from foveal vision (directly fixated words) during sentence reading in the deaf teenagers. The results showed that deaf teenagers showed a pseudohomophone advantage, providing evidence for phonological coding of fixated words during sentence reading in deaf teenagers.

The lack of consistency across previous findings in relation to phonological coding in the deaf could be partially accounted for by many factors that include individual differences, differences in task demands, and the transparency of the language system, amongst others (Hirshorn, Dye, Hauser, Supalla, & Bavelier, 2015; McQuarrie & Parrila, 2008).

In the present study we adopt an error disruption paradigm, which allows us to examine the phonological processing of text during natural sentence reading. In the error disruption paradigm, participants read each sentence with either a correctly spelled word (e.g. He wore blue jeans), a homophone (e.g. He wore blew jeans) or a spelling control word (e.g. He wore blow jeans) (Jared & O'Donnell, 2017). The rationale is that, substitutions (e.g., homophones), which preserve similar features with the correctly spelled word, should be less disruptive to reading compared to unrelated spelling control words, to the extent that readers rely on certain features (e.g. phonology) to aid reading (Daneman & Reingold, 1993). Studies using this paradigm have observed phonological coding during sentence reading in hearing students (Blythe, Pagán, & Dodd, 2015; Jared, Ashby, Agauas, & Levy, 2016; Rayner, Pollatsek, & Binder, 1998), and also in deaf readers (Blythe, Dickins, Kennedy, & Liversedge, 2018) in western populations.

Unlike alphabetic writing systems, Chinese is a writing system with deep orthography, and the orthography–phonology mapping of Chinese characters is not always consistent and regular (Zhou & Marslen-Wilson, 2000). Two Chinese characters with the same pronunciation can be completely different in orthography, for example,

阳 (yang, the tone is second) and 洋 (yang, the tone is second). Thus, Chinese materials offer a unique opportunity to eliminate the confound between grapheme and phoneme associations in alphabetic languages. Feng, Miller, Shu, and Zhang (2001) have shown that hearing Chinese college students take advantage of phonological features in reading using the error disruption paradigm. Their findings suggest that phonological information helps hearing readers to recover from disruptive effects of making errors.

The study of Yan, Pan, Bélanger, and Shu (2015), the first to investigate the phonological coding of Chinese deaf readers (using a boundary paradigm) during Chinese sentence reading, reported that more-skilled Chinese deaf readers were able to process parafoveal phonological information. The current study adopts the error disruption paradigm which offers the advantage of permitting an investigation of foveal phonological processing during natural sentence reading in Chinese deaf readers.

In the current study, on the basis of previous studies with hearing participants, (Feng et al., 2001; Zhou, Shu, Miller, & Yan, 2017), both groups of hearing readers (chronological age-matched (CA) and reading ability-matched (RA) hearing readers) would be predicted to show shorter reading times on homophones than on spelling control words (a homophone advantage), reflecting activation of phonological coding during sentence reading. If deaf students fail to activate phonological coding during sentence reading, an absence of a homophone advantage (shorter reading times on homophones) would be predicted for the deaf group.

Method

Participants

There were three participant groups, namely, deaf middle school students (DS); chronological age-matched (CA) controls; and reading ability-matched (RA) controls, with 34 participants in each group. The DS were severely to profoundly deaf (hearing loss above 80 dB in their better ear) and all wore hearing aids. None had received a cochlear implant. Deaf participants were born deaf or they became deaf before the age of three, used Chinese sign language as their main language for communication, and were aged from 13.7 to 20.0 years (M = 17.37, SD = 1.74). Deaf participants were educated in a school for the deaf, and they were all taught sign language from the age of six years at school. All deaf participants were proficient in sign language and all were learning to read written Chinese. The parents of the deaf participants all had normal hearing.

All participants in CA and RA controls had normal hearing. The CA controls were aged from 13.42 to 20.8 years (M = 16.86 years, SD = 2.14) were matched to the DS on chronological age (t = -1.12, p > 0.05). The RA controls were aged from 10.16 to 11.72 years (M = 10.74, SD = 0.34), and were matched to the DS on reading fluency, reading comprehension and nonverbal IQ (see Table 1 for tests used and summary scores). The reading fluency test requires readers to read and comprehend simple sentences and to judge the contents as rapidly as possible within a three minute time frame by ticking a box at the end of each sentence to indicate whether the information is correct or incorrect (for example, ‘the sun rises in the west’; Pan et al., 2011; Lei et al., 2011). The number of characters marked with correct sentences within 3 minutes is calculated as the dependent variable. For reading comprehension, participants were asked to answer multiple choice questions or subjective questions after reading a short essay (Li, Wu, Zhou, Chen, & Nguyen, 2016). Raven's Standard Progressive Matrices were administered (Raven, Court, & Raven, 1996) to measure nonverbal IQ.

--TABLE 1--

Material and Design

A total of 45 two-character target words were created and embedded into sentence frames. Two fourth grade teachers from Tianjin Primary School and two middle school teachers from Tianjin Deaf School proofread the sentences and reported no unfamiliar words for the students. The first character of each target word was replaced by either an identical character (e.g., 阳光, the pronunciation is Yang, the tone is second), a homophone (the homophone share the pronunciation with the identical character, e.g., 洋光, the pronunciation is Yang, the tone is second) or an unrelated substitution (the unrelated substitution was different from the identical character in spelling, pronunciation and meaning, e.g., 绝光, the pronunciation is Jue, the tone is second). Table 2 shows a summary of the linguistic property measures that the three types of substitutions were matched on: (1) character frequencies, F (2, 118) = 0.49, p > 0.05, (2) visual complexity indexed by number of strokes, F (2, 118) = 1.06, p > 0.05.

--TABLE 2--

Rating Studies: A total of 40 fourth graders were invited to conduct two norming studies to ensure that the sentences were neutral. Firstly, the predictability of the targets was assessed based on sentence constraint ratings. Half of the 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. The mean score of the sentences was 5% (*SD* = 0.09), indicating that all target words in the sentences were low on predictability. Secondly, sentence difficulty was assessed on a five-point scale (e.g., a score of “5” was “very difficult” to understand). Half of the participants were presented with complete sentences with the correct target word and asked to rate each one. The mean score of the sentences was 1.24 (*SD* = 0.24), indicating that all sentences were appropriate given the reading level of the participants.

The experimental sentences had a length of 14 to 17 characters (*M* = 15.15, *SD* = 1.00). The target words consisted of two characters which never appeared among the first four or the last four characters. Each sentence was presented only once to each participant, with all of the conditions counterbalanced. Each participant read 45 sentences (15 per condition), which were randomly presented during the experiment. The sentences used in the experiment are presented in full in Appendices 1.

Apparatus

An EyeLink 2000 (SR Research Ltd.) eye tracker was used to record the readers’ eye movements, and the sampling rate was 1000 Hz. All calibrations and recordings were based on the right eye only. Single-line sentences were displayed on a ViewSonic G220f 21-inch CRT monitor (refresh rate, 120 Hz; resolution, 1024 × 768 pixels) at a viewing distance of 65 cm. Characters were displayed using the font Song 28 and each character subsumed 0.9° of visual angle.

Procedure

Participants were seated comfortably, and then a three-point horizontal calibration and validation procedure was conducted. If the individual mean validation error or the error for any one of the points was greater than 0.2°, then the procedure was repeated. The first nine trials were practice trials with three easy yes–no questions related to the meaning of the sentences. Participants were presented with a single sentence at a time and were instructed to read the sentences silently, and to press a button on the gamepad once they had finished reading. On one-third of the trials, the sentence was followed by a comprehension question, to which participants responded yes or no using a button on the gamepad. Participants were informed that some of the words might be misspelled, but they should simply do their best to understand the sentence. The overall experimental session lasted for approximately 15 minutes.

Data analysis

Following convention (Bai, Yan, Liversedge, Zang, & Rayner, 2008), a data reduction procedure combined short fixations (shorter than 40 ms) with nearby fixations, after which fixations shorter than 80 ms or longer than 1200 ms were removed. Trials, in which sentences received less than three fixations were deleted (affecting approximately 2.3 %), as well as trials, in which scores were more than three SD's from each participant's mean (FFD:1.4%; GD: 1.8%; RP: 2.0%; TT: 1.2%). Similar to previous studies in Chinese (e.g. Zhou et al., 2017), data analyses were performed within two-character word regions for the target words.

Three early-stage processing and two late-stage processing eye movement measures, defined according to Jared & O'Donnell (2017) and Friesen, Whitford, Titone, & Jared (2020), were examined. Early-stage measures reflect early lexical identification of a word, and include First Fixation Duration (FFD) which is the duration of the first fixation on a word regardless of how many other fixations were made, Gaze Duration (GD) which is the sum of all fixations on a word prior to moving on to a different word, including refixations, and Regression out, which is the probability of regressing out of a word to an earlier word. Late-stage measures reflect later integration processing of the sentences and later lexical identification, and include Regression Path Time (RP) which is the sum of all fixation durations on a region from first entering the region until going past that region, and Total Reading Time (TT) which is the sum of all fixations on a word throughout the duration of the trial. Although skipping rates were also examined, there were no significant differences between the homophones and unrelated words (b = 0.05, SE = 0.11, z = 0.42); thus, detailed analyses are not reported. Each measure is reported for the analyses of target words in the sentences.

If phonological coding occurs in the early lexical identification stage, we should observe that participants' FFD on homophones are shorter than FFD on unrelated words, that participants' GD on homophones are shorter than GD on unrelated words, and that participants produce fewer regression out for homophones compared to unrelated words. If phonological coding is activated during sentence integration processing, we should observe that participants produce less RP for homophones compared to unrelated words, and if phonological coding occurs in the later lexical identification stage, we should observe that participants' TT on homophones are shorter than TT on unrelated words.

Analyses were performed with liner-mixed effects models (Bates, Maechler, & Dai, 2009) within the R environment (R Development Core Team, 2012). For each variable, fixed effects included Group and Word Type, and random effects included random intercepts for participants and items, random slopes for Word Type across participants, and random slopes for Word Type and Group across items. If the initial model failed to converge then the random structure was incrementally trimmed, beginning with the items level. The model was run on log-transformed reading time. Logistic generalized linear mixed models (GLMMs) were used for the regression data and skip data. We report regression coefficients (*b*), standard errors (*SE*), and t values or z values (t or $z = b/SE$). A two-tailed criterion ($|t|$ or $|z| \geq 1.96$) was used to determine significance. The error disruption paradigm assumes that if readers activate the meanings of words using phonological coding, then homophones should produce shorter reading times compared to reading times on unrelated words. So, we mainly focus on the differences in reading times (for all eye movement measures) between homophones and unrelated words.

Results

Deaf students compared with control groups

Four participants from the DS, three from the RA controls, and one from the CA controls were excluded from the data analysis because their response accuracy for comprehension questions was below 70%. The accuracy of the comprehension questions by the participants included in the analyses was 90% (RA controls), 89% (DS) and 95% (CA controls). A one-way analysis of variance (ANOVA) showed that the difference in reading accuracy of the three groups was significant [F (2, 93) = 5.78, $p < 0.05$]. Post-hoc tests found that the RA controls had a significantly lower reading accuracy than the CA students ($p < 0.05$), and the deaf students' reading accuracy was lower than the CA controls ($p < 0.05$). In general, all three groups had high accuracy demonstrating and understanding of the meaning of the sentences.

Means for each eye movement measure, broken down by participant group and experimental condition are shown in Table 3. We ran the model with group (RA, DS, CA), and word type (correctly spelled words, homophones, unrelated words) as fixed factors. The results of this model for the eye movement measures are shown in Table 4.

--TABLE 3—

--TABLE 4—

Early-stage measures

There was no significant difference between homophones and unrelated words in FFD and GD, and no interaction between group and word type (homophones vs. unrelated words) in FFD and GD, indicating that neither of the three groups showed an early processing homophone advantage. In the group main effects, the difference was not significant for group in FFD. The RA controls' GD was significantly longer than the DS' GD. However, there was no significant difference between the DS and CA controls in GD.

A significant effect of word type (homophones vs. unrelated words) was found in regression out. Fewer regressions out occurred for homophones than for control words. The group (RA vs. DS) and word type (homophones vs. unrelated words) interaction was marginal significant, but the group (DS vs. CA) and word type (homophones vs. unrelated words) interaction was not significant. For the DS, there was no significant homophone advantage (b = -0.05, SE = 0.22, z = -0.22). For the RA controls, there was a significant homophone advantage (b = -0.52, SE = 0.16, z = -3.34), fewer regressions out occurred for homophones than for control words. In the group main effects, fewer regressions out occurred for the DS than for both controls.

Late-stage measures

A significant difference between homophones and unrelated words was observed in RP and TT. Homophones were fixated for a shorter time than unrelated words. The group (RA vs. DS) and word type (homophones vs. unrelated words) interaction was significant in RP and TT. The group (DS vs. CA) and word type (homophones vs. unrelated words) interaction was not significant in RP but was significant in TT. In RP, for the CA controls and the DS, there was no significant homophone advantage (CA: b = -0.07, SE = 0.04, t = -1.61; DS: b = 0.00, SE = 0.04, t = 0.07), for the RA controls, there was a significant homophone advantage (b = -0.20, SE = 0.05, t = -3.86). In TT, for the CA and the RA, there was a significant homophone advantage (CA: b = -0.24, SE = 0.04, t = -6.54; RA: b = -0.25, SE = 0.04, t = -6.52), but for the DS, there was no significant homophone advantage (b = -0.02, SE = 0.04, t = -0.52). In the group main effects, the reading time of RA controls was significantly longer than the DS in RP and TT. However, there was no significant difference between the DS and CA controls in RP and TT.

In summary, and as shown in Table 4, a significant homophone advantage was observed for both control groups in TT. Homophones were fixated for significantly shorter durations than unrelated words, and we also found that the RA controls showed a significant homophone advantage in regression out and RP. However, For the DS group, there was no evidence for a significant homophone advantage in all eye movement measures.

The results clearly show that reading ability can impact upon performance in the current experiment, and that the RA group had more regressions out, longer GD, longer RP, and longer TT in comparison to the DS group. Additionally, the RA group showed a homophone advantage in the regression out, the RP, and the TT measures. However, it should be noted that the deaf students in the current study had large individual differences in reading ability, and these were not controlled for in the initial analyses of the data. Therefore, reading ability within the DS group could be a factor that affects whether phonological coding is activated during sentence reading in the deaf. For example, previous studies have found that the use of phonological information is related to the reading level of deaf readers (Perfetti & Sandak, 2000; Wang, Trezek, Luckner, & Paul, 2008). Furthermore, Yan et al. (2015) have found that more-skilled Chinese deaf readers show a phonological preview benefit compared to less-skilled Chinese deaf readers (the test of classification was reading fluency). In order to examine whether Chinese deaf students' individual differences in reading level are related to the use of phonological coding, we divided the deaf students in the current study into more-skilled and less-skilled readers, according to reading fluency (the fluency test needed participants to make a value judgment following each sentence, and hence this test also includes comprehension).

More-skilled deaf students compared with less-skilled deaf students

In line with a previous study (Häikiö, Bertram, Hyönä, & Niemi, 2009), we used a median split procedure to categorize the deaf student participants into two subgroups, based on their silent-reading fluency score. The median (score = 310.67) is the standard cut off point for characterising readers as being more-skilled or less-skilled. Using that criteria we divided the sample of deaf students into less-skilled (LSKD) and more-skilled (MSKD) students, and the reading fluency of these two subgroups was significantly different (t = -7.36, p < 0.001), the reading comprehension was significantly different (t = -3.06, p < 0.05), but the IQ and age of these two subgroups was not significantly different (IQ: $t = -0.24$, $p > 0.05$; age: $t = 0.84$, $p > 0.05$). Means for each dependent measure, broken down by participant group and experimental condition, are shown in Table 5. We then ran a linear mixed-effects model with group (MSKD vs. LSKD), and word type (homophone vs. unrelated) as fixed factors. The results of this model for the eye movement measures are shown in Table 6.

--TABLE 5—

--TABLE 6--

Early-stage measures

There was no significant difference between homophones and unrelated words in FFD, GD, and regression out. The difference was not significant for group in FFD, GD, and regression out. The interaction between group and word type was not significant in FFD and regression out, however, it was significant in GD. For the MSKD, there was no significant homophone advantage ($b = -0.09$, $SE = 0.05$, $t = -1.71$), and for the LSKD, there was no significant homophone advantage ($b = 0.08$, $SE = 0.05$, $t = 1.68$).

Late-stage measures

There was no significant difference between homophones and unrelated words in RP and in TT. The difference was not significant for group in RP, however, the group main effect was significant in TT, the MSKD’s TT were longer than the LSKD. The interaction between group and word type was not significant in RP, but the interaction was significant in TT. For the MSKD, there was a marginal significant homophone advantage ($b = -0.10$, $SE = 0.05$, $t = -1.94$), whereas for the LSKD, there was no significant homophone advantage ($b = 0.06$, $SE = 0.05$, $t = 1.12$).

In summary the results provide evidence of a homophone advantage in the MSKD for the TT measure. These data are presented in Figure 1. The evidence for this advantage was then verified by comparing the MSKD with the two control groups in the study. This comparison showed that the group (RA vs. MSKD) and word type (homophone vs. unrelated) interaction was not significant in RP (b = 0.13, SE = 0.09, t = 1.42), however it was significant in TT (b = 0.16, SE = 0.07, t = 2.11), and the group (MSKD vs. CA) and word type (homophone vs. unrelated) interaction were not significant in RP and TT (RP: b = 0.01, SE = 0.09, t = 0.12; TT: b = -0.13, SE = 0.07, t = -1.80). The findings from this comparison suggests that the MSKD group were equivalent to the CA group and the RA group in showing a TT homophone advantage, but this advantage was a smaller than the one shown by the RA group. This is likely to reflect more regressions being made by the younger RA group, as reported earlier.

More-skilled RA students compared with less-skilled RA students

Since the deaf students were matched on reading ability to the RA group, we also divided the RA group into more-skilled and less skilled readers, and we compared these two sub-groups (the results are presented in Appendices 3). Both subgroups showed a homophone advantage.

--FIGURE 1—

Discussion

This study investigated the role of phonological coding during sentence reading in Chinese deaf middle school students. For the RA group, homophones produced significantly shorter regression path time and total reading time than unrelated words, and homophones produced less regression out than unrelated words. For the CA group, homophones produced significantly shorter total reading time than unrelated words. These data indicated that both chronologically age matched, and reading ability matched groups showed a homophone advantage. There was no evidence of a homophone advantage in the deaf students. However, when the deaf students were divided into more-skilled and less-skilled students, the homophone advantage was observed for the more-skilled deaf students, and this advantage was absent in the less-skilled deaf students. Overall, our analysis of the data for the two subgroups of deaf students (more-skilled and less-skilled) provide evidence to suggest that more-skilled deaf students use phonological coding during sentence reading, whereas less-skilled deaf students do not.

This study found significant differences between homophones and unrelated words in the later eye movement measures (total reading time) for hearing control groups, and the total reading time on homophones was remarkably shorter than those for unrelated words. This indicates that phonological coding occurs at the later lexical identification stage in typical students reading Chinese sentences. However, we also found the RA controls showed a homophone advantage in the regression out and the regression path time measures, whereas the CA controls did not. We interpret this finding to indicate that phonological information may play an important role in the integration process of sentences for the CA controls. However, the RA controls who were much younger hearing students showed a homophone advantage for both early and later lexical identification measures. These time course differences in the control groups may simply be related to age, since Chinese readers who are at the early stages of learning to read, are taught using hanyu pinyin (Yan, Miller, Li, & Shu,2008) and have been proposed to rely on phonological mediation, unlike skilled readers who have been shown to have more direct access to semantics from orthography (Zhou et al., 2017).

In the present study, the hearing students were composed of primary and middle school students. The current findings show that both primary school and middle school students can process phonology during lexical identification in silent sentence reading. Therefore, for hearing students, the results from the current study extend previous findings on phonological activation of word meanings during reading, and they support the evidence for a benefit in later eye movement measures for college students (Feng et al., 2001; Wong & Chen, 1999).

In general, the present study showed no significant differences between homophones and unrelated words in all eye movement measures for the deaf students when they were analysed as a single group. This finding would seem to support the viewpoint that deaf students cannot activate phonological coding during silent sentence reading (Bélanger et al., 2012; Fariña, et al., 2017). However, there are large individual reading ability differences in the deaf, and Mayberry et al. (2011) have emphasised that in studies of deaf readers, few studies control for individual differences in reading levels within the deaf group. When the deaf students in the current study were divided into more-skilled and less-skilled students, a similar homophone advantage was observed for the total reading time measures, and this advantage was exclusive to the more skilled readers amongst the deaf students. Therefore, the statement above that suggested that deaf readers do not activate phonological coding has been qualified to now refer to less skilled deaf readers. Consistent with previous research (Daigle & Armand, 2007; Furlonger, Holmes, & Rickards, 2014; Hanson & Fowler, 1987), our results showed that the use of phonology is associated with higher levels of reading skill in Chinese deaf readers. This is not the case for the RA controls in this study, since both more skilled and less skilled readers in that group showed a homophone advantage (see Appendices 3). Therefore, it is not reading ability per se that prevents the use of phonological coding in the less skilled deaf readers in this study.

Since the more skilled deaf readers showed the same effects for the homophones as the control groups, we can infer that they have made use of phonological coding during reading sentences in this experiment. However, the less skilled deaf readers did not show the homophone advantage, indicating that they were unable to use phonological coding when they read the sentences. An obvious question relates to why less skilled deaf readers are unable to activate phonological coding during sentence reading. Morford, Kroll, Piñar, and Wilkinson (2014), Meade, Midgley, Sehyr, Holcomb, and Emmorey (2017) found that deaf readers who were less skilled in their English were more likely to use sign translations. It could therefore be the case that the less skilled deaf readers rely on sign phonology during reading, and the more skilled deaf readers rely on sound phonology. The reason that there are shorter reading times and regressions for homophones, compared to unrelated words, is that the homophones share the same sound phonology as the correctly spelled words. The literature suggests that deaf readers do engage in sign phonology during reading (Bélanger, Morford, & Rayner, 2013; Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Ormel, Hermans, Knoors, & Verhoeven, 2012; Pan, Shu, Wang, & Yan, 2015; Treiman & Hirsh-Pasek, 1983). However, it is not known whether deaf readers who engage in sign phonology during reading are less skilled deaf readers. What is known is that if readers are using sign phonology, then one would not expect to see the homophone advantage during reading, as there is no equivalent sign phonology for written homophones. Specifically, sign phonology includes four formational parameters: handshape, location, movement, and orientation (Battison, 1978; Stokoe, Croneberg, & Casterline, 1965), and sign-phonological relatedness has been defined as sharing at least two formational parameters (Ormel et al., 2012). In the present study, the sign phonology of target characters in the sentences do not share any two sign formational parameters. This means that, in the current study, there is no equivalent sign phonology for the written homophones.

A further question that arises from the findings in the present study relates to what underpins whether a deaf person becomes a more skilled or a less skilled reader. According to Musselman (2000), if the reading processing of the more-skilled deaf reader is similar to that of hearing readers, we can speculate that the reason for difficulty in reading in that group is due to a delay in their reading development, caused by hearing loss. However, if the reading processing of the less-skilled deaf reader is different to that of hearing readers, and, if that group relies more on sign language representation in the reading process (see Bélanger et al., 2012; Sterne & Goswami, 2000), then we can infer that the reason for difficulty in reading in the less skilled readers may reflect atypical (rather than delayed) reading development.

In summary, the results of the present study have important theoretical implications as they suggest that not all deaf readers develop reading skills in the same way. If it is the case that less-skilled deaf students rely more on sign phonology, this could prevent them from being able to use phonological coding during reading. The results also have important practical implications for the teaching methods of deaf readers. Methods designed to improve reading may have to be tailored for deaf students who may rely more on sign phonology, since these students may need to be taught to develop and build the connections between the written language forms and sign language.

Conclusion

This investigation of phonological coding in deaf Chinese readers has shown that more-skilled Chinese deaf readers use phonological coding during sentence reading, whereas less-skilled Chinese deaf readers do not. We hypothesise that reading difficulties in Chinese more-skilled deaf students may be due to delayed reading development, whereas reading difficulties in Chinese less-skilled deaf students may reflect atypical reading development, but we concur that these hypotheses remain to be empirically tested. What is of further interest for future research is to investigate why some deaf readers are able to activate phonological coding during reading, whereas other are not.

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Ethics approval

This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Research Ethics Committee at Tianjin Normal University. Participants' legal guardians gave informed consent and each participant provided written informed consent before taking part in the study.

Conflict of interest

The authors declare no conflict of interest.

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Appendices 1

In this section, we document our experiment materials. Target words are formatted in bold.

item	sentence	Correctly spelled	Homophone	Unrelated
1	明亮温暖的**阳光**轻轻地洒落在草原上。	阳	洋	绝
2	为家人做饭是一件**轻松**愉快的事情。	轻	清	格
3	王小明一想到**减法**就会感到头疼。	减	检	顾
4	自然界有很多**奇怪**的现象在等我们发现。	奇	齐	冬
5	清晨的荷叶上挂着很多**晶亮**的小水珠。	晶	惊	预
6	园丁说把这种**兰花**种在花园里会更好。	兰	蓝	票
7	小军很喜欢**夏天**荷花盛开的景象。	夏	吓	巩
8	童年时在**乡下**的日子是我难忘的回忆。	乡	香	免
9	长大后成为**医生**是我儿时的梦想。	医	衣	含
10	清洁工人把**校园**打扫得非常干净。	校	笑	爱
11	那支长长的队伍行走在**冰天**雪地里。	冰	兵	号
12	妹妹被一阵**响声**吓得不敢出门了。	响	享	弃
13	我已经忘记这座**城市**是什么样子了。	城	承	穿
14	刘老师领着我走到了**班级**的讲台中央。	班	般	持
15	听说王叔叔**住在**这个小区的东北角。	住	助	材
16	这个小学校有很多**姓名**相同的人。	姓	兴	乐
17	我们从河里一共**捕到**了十条小鱼。	捕	补	陆
18	这个小店的**蛋糕**很受学生们的欢迎。	蛋	淡	绪
19	每一个人都应该**保护**可爱的野生动物。	保	宝	序
20	一束温暖的阳光**照进**了我的房间。	照	赵	购
21	这片树林里的**叶子**在风中沙沙作响。	叶	夜	府
22	我相信这片**李子**树明年就能开花结果。	李	礼	伙
23	这家商店的员工**服务**又周到又热情。	服	福	端
24	山谷里的**河水**叮叮咚咚地响了起来。	河	核	培
25	一只小猫正在**石头**上安静地睡觉。	石	识	规
26	这件新衣服的**布料**又漂亮又舒服。	布	步	至
27	校园里的梅花在**冬天**开出了美丽的花朵。	冬	东	区
28	这个著名**歌手**的声音非常的好听。	歌	割	峰
29	小杰新买的**背包**看起来漂亮极了。	背	悲	赏
30	田野里的**谷物**到了秋天都会变成黄色的。	谷	古	台
31	王老师家里有**急事**所以不能来上课了。	急	级	话
32	白雪公主一直**记得**那个帮助过她的人。	记	计	设
33	花花一个人坐在**树下**给弟弟洗衣服。	树	数	题
34	军人每年和**亲人**见面的次数很少。	亲	侵	损
35	公园里每年春天的**景色**都非常美丽。	景	井	贝
36	夜晚的学校**阴森**森的让他们感到害怕。	阴	音	觉
37	弟弟在河边光着**脚丫**等妈妈一起回家。	脚	角	考
38	小花狗正向拿着**骨头**的我摇尾巴。	骨	股	洞
39	学校把学生活动的**场所**放在了体育场。	场	厂	毛

40	他觉得这门**课程**的考试非常困难。	课	客	虽
41	家中唯一的**洗衣**机被阿朵弄坏了。	洗	喜	简
42	在温暖的窝里**沉睡**的小猫非常可爱。	沉	陈	词
43	要想成为一名**画家**是需要自己多努力的。	画	划	约
44	小姑娘决定剪掉那一头**乌黑**发亮的头发。	乌	屋	贵
45	医学专家说**鸡肉**对病人的身体有好处。	鸡	击	巴

Appendices 2

In this section, we document results for the correctly spelled condition.

Early-stage measures

Correctly spelled words vs. homophones

Correctly spelled words were fixated shorter than homophones in FFD (b = 0.07, SE = 0.02, t = 4.77), and GD (b = 0.21, SE = 0.02, t = 9.42). The interactions between group (RA vs. DS) and word type were not significant in FFD (b = -0.06, SE = 0.04, t = -1.69), however, in GD were significant (b = -0.17, SE = 0.05, t = -3.08). The interactions between group (DS vs. CA) and word type were significant in FFD (b = 0.08, SE = 0.04, t = 2.02), and GD (b = 0.13, SE = 0.06, t = 2.35). In regression out, there was no significant difference between correctly spelled words and homophones (b = 0.20, SE = 0.11, z = 0.07). The interactions between group and word type were not significant ($|z| < 0.75$).

Correctly spelled words vs. unrelated words

Correctly spelled words were fixated shorter than unrelated words in FFD (b = -0.06, SE = 0.02, t = -3.80), and GD (b = -0.22, SE = 0.02, t = -9.91). The interactions between group (RA vs. DS) and word type were not significant in FFD (b = 0.03, SE = 0.04, t = 0.84), however, in GD were significant (b = 0.21, SE = 0.05, t = 3.89). The interactions between group (DS vs. CA) and word type were not significant in FFD (b = 0.04, SE = 0.04, t = 1.07), however, in GD were significant (b = 0.12, SE = 0.06, t = 2.12). In regression out, correctly spelled words produced less regression out than unrelated words (b = 0.52, SE = 0.11, z = 4.74). The interactions between group (RA vs. DS) and word type were significant (b = 0.63, SE = 0.28, z = 2.27), however, the interactions between group (DS vs. CA) and word type were not significant (b = -0.54, SE = 0.29, z = -1.86).

Late-stage measures

Correctly spelled words vs. homophones

Correctly spelled words were fixated shorter than homophones in RP (b = 0.27, SE = 0.03, t = 9.89), and TT (b = 0.42, SE = 0.03, t = 15.20). The interactions between group and word type were significant in RP ($|ts|$ > 3.16), and TT ($|ts|$ > 2.06).

Correctly spelled words vs. unrelated words

Correctly spelled words were fixated shorter than unrelated words in RP (b = -0.35, SE = 0.03, t = -12.79), and TT (b = -0.59, SE = 0.02, t = -26.55). The interactions between group and word type were significant in RP ($|ts|$ > 4.21), and TT ($|ts|$ > 6.40).

Appendices 3

In this section, we document results for the more-skilled and less-skilled RA group. We divided the RA group into more-skilled and less-skilled readers in terms of their reading fluency. We then ran a linear mixed-effects model with group (MSKD vs. LSKD), and word type (homophone vs. unrelated) as fixed factors. The results showed that the interactions between group and word type were not significant in FFD (b = 0.09, SE = 0.06, t = 1.45), GD (b = 0.08, SE = 0.09, t = 0.82), regression out (b = 0.47, SE = 0.33, z = 1.43), RP (b = 0.17, SE = 0.11, t = 1.61), and TT (b = 0.06, SE = 0.08, t = 0.79).

Table 1

Nonverbal IQ, reading fluency, reading comprehension, and age for RA and DS groups.

	RA	DS	MSKD	LSKD	*t*
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	
Nonverbal IQ (standardised)	59.50 (23.23)	50.84 (21.01)	53.14 (22.48)	46.69 (19.27)	1.67
Reading fluency (characters/min)	297.00 (182.10)	295.72 (143.77)	428.40 (103.49)	200.29 (60.84)	0.04
Reading comprehension (score)	8.84 (2.16)	8.37 (3.42)	10.43 (2.82)	7 (3.31)	0.65
Age (years)	10.74 (0.34)	17.37 (1.74)	17.31 (1.96)	17.82 (1.38)	-20.87

Note: DS group included More-skilled DS (MSKD) and Less-skilled DS (LSKD). The t tests were contrasted between RA and DS groups.

Table 2

Character properties of the three experimental conditions

	Correctly spelled *M* (*SD*)	Homophone *M* (*SD*)	Unrelated *M* (*SD*)
Character	阳	洋	绝
Pronunciation	Yang2	Yang2	Jue2
Frequency	269.04 (21.89)	245.42 (25.30)	245.46 (25.21)
No. of strokes	8.24(0.31)	8.75 (0.42)	8.64 (0.39)

Note. Means (and standard deviation [*SD*]) of frequency per million (Beijing Language Institute, 1986) and number of strokes are provided in the table. The target word (阳光, sunshine) is embedded into a sentence (明亮温暖的**阳光**轻轻地洒落在草原上), which is translated as: The bright and warm *sunshine* falls gently on the grassland.

Table 3

Means and Standard Deviations for eye movement measures for the RA, DS, and CA groups.

	RA			DS			CA		
	CO	HO	UN	CO	HO	UN	CO	HO	UN
FFD (ms)	273 (124)	302 (142)	298 (151)	268 (113)	275 (118)	276 (111)	237 (90)	268 (110)	261 (114)
GD (ms)	371 (243)	520 (367)	566 (423)	339 (204)	380 (230)	380 (222)	278 (143)	379 (228)	387 (273)
Regression out	0.25 (0.43)	0.29 (0.44)	0.40 (0.49)	0.14 (0.35)	0.15 (0.36)	0.16 (0.36)	0.17 (0.38)	0.22 (0.41)	0.28 (0.45)
RP (ms)	584 (494)	879 (753)	1045 (777)	431 (310)	495 (372)	488 (361)	371 (278)	542 (390)	620 (496)
TT (ms)	640 (440)	1084 (668)	1428 (907)	540 (342)	732 (528)	725 (470)	426 (265)	659 (413)	841 (508)
Skip	0.18 (0.38)	0.15 (0.35)	0.12 (0.33)	0.20 (0.40)	0.16 (0.37)	0.20 (0.40)	0.24 (0.43)	0.21 (0.41)	0.19 (0.39)

Note: CO = correctly spelled words, HO = homophone words, UN = unrelated words.

Table 4

Results from LMMs for eye movement measures for the RA, DS, and CA groups.

	First fixation duration			Gaze duration			Regression out			Regression path time			Total reading time		
	b	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*z*	*b*	*SE*	*t*	*b*	*SE*	*t*
Intercept	5.51	0.02	287.00	5.77	0.03	187.52	-1.41	0.10	-13.65	6.08	0.04	164.50	6.41	0.04	182.51
DS-RA	-0.05	0.05	-1.16	**-0.21**	**0.07**	**-2.90**	**-1.04**	**0.22**	**-4.71**	**-0.47**	**0.08**	**-5.64**	**-0.41**	**0.08**	**-5.17**
CA-DS	-0.07	0.05	-1.58	-0.08	0.07	-1.08	**0.52**	**0.22**	**2.35**	0.02	0.08	0.26	-0.06	0.08	-0.79
HO-CO	**0.07**	**0.02**	**4.77**	**0.21**	**0.02**	**9.42**	0.20	0.11	0.07	**0.27**	**0.03**	**9.89**	**0.42**	**0.03**	**15.20**
CO-UN	**-0.06**	**0.02**	**-3.80**	**-0.22**	**0.02**	**-9.91**	**-0.52**	**0.11**	**-4.74**	**-0.35**	**0.03**	**-12.79**	**-0.59**	**0.02**	**-26.55**
HO-UN	0.02	0.02	0.99	-0.01	0.02	-0.52	**-0.32**	**0.11**	**-3.00**	**-0.09**	**0.03**	**-3.20**	**-0.17**	**0.02**	**-7.15**
DS-RA × HO-CO	-0.06	0.04	-1.69	**-0.17**	**0.05**	**-3.08**	-0.15	0.28	-0.53	**-0.25**	**0.07**	**-3.63**	**-0.26**	**0.07**	**-3.87**
DS-RA × CO-UN	0.03	0.04	0.84	**0.21**	**0.05**	**3.89**	**0.63**	**0.28**	**2.27**	**0.45**	**0.07**	**6.64**	**0.50**	**0.05**	**9.02**
DS-RA × HO-UN	-0.03	0.04	-0.86	0.05	0.05	0.83	0.49	0.27	1.81	**0.20**	**0.07**	**3.04**	**0.23**	**0.06**	**4.02**
CA-DS × HO-CO	**0.08**	**0.04**	**2.02**	**0.13**	**0.06**	**2.35**	0.22	0.29	0.75	**0.21**	**0.07**	**3.16**	**0.14**	**0.07**	**2.06**
CA-DS × CO-UN	-0.04	0.04	-1.07	**-0.12**	**0.06**	**-2.12**	-0.54	0.29	-1.86	**-0.29**	**0.07**	**-4.21**	**-0.35**	**0.05**	**-6.40**
CA-DS× HO-UN	0.04	0.04	0.96	0.01	0.05	0.22	-0.34	0.28	-1.23	-0.07	0.07	-1.09	**-0.21**	**0.06**	**-3.68**

Note: Model with group (RA, DS, CA), word type (correctly spelled words (CO), homophone words (HO), unrelated words (UN)) as fixed factors. Statistically–significant t-values are formatted in bold.

Table 5

Means and Standard Deviations for eye movement measures for the MSKD and LSKD groups.

	MSKD			LSKD		
	CO	HO	UN	CO	HO	UN
FFD (ms)	246 (104)	261 (106)	264 (97)	286 (117)	288 (127)	286 (120)
GD (ms)	279 (164)	336 (199)	370 (216)	389 (221)	421 (248)	389 (228)
Regression out	0.18 (0.38)	0.16 (0.37)	0.19 (0.39)	0.11 (0.31)	0.14 (0.35)	0.13 (0.33)
RP (ms)	392 (316)	461 (379)	492 (377)	464 (301)	526 (365)	484 (348)
TT (ms)	524 (384)	805 (643)	850 (560)	556 (294)	660 (367)	601 (316)

Note: CO = correctly spelled words, HO = homophone words, UN = unrelated words

Table 6

Results from LMMs for eye movement measures for the MSKD and LSKD groups.

	First fixation duration			Gaze duration			Regression out			Regression path time			Total reading time		
	b	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*z*	*b*	*SE*	*t*	*b*	*SE*	*t*
Intercept	5.56	0.06	99.89	5.79	0.08	72.91	-2.16	0.34	-6.33	5.97	0.10	61.06	6.25	0.10	62.83
Group	-0.07	0.08	-0.89	-0.06	0.11	-0.50	0.55	0.45	1.22	-0.02	0.14	-0.17	**0.29**	**0.14**	**2.10**
Word type	0.01	0.04	0.38	0.08	0.05	1.67	0.03	0.36	0.08	0.07	0.06	1.13	0.06	0.05	1.01
Interaction	-0.04	0.05	-0.73	**-0.17**	**0.07**	**-2.39**	-0.16	0.45	-0.36	-0.14	0.09	-1.54	**-0.16**	**0.08**	**-2.03**

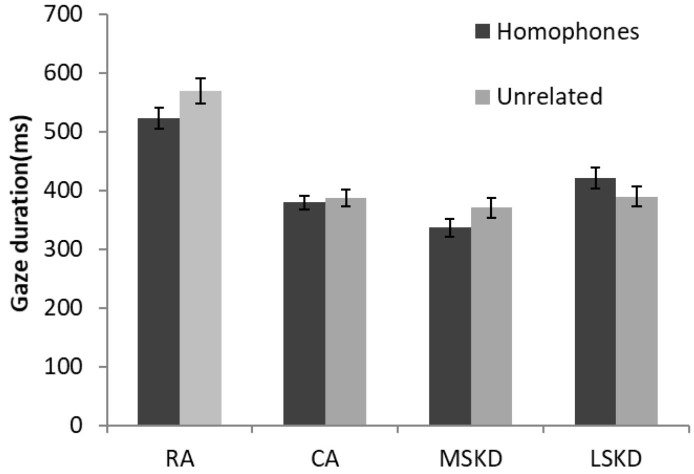
Note: Model with group (MSKD, LSKD), word type (homophone words, unrelated words) as fixed factors. Statistically–significant t-values are formatted in bold.

Figure Captions

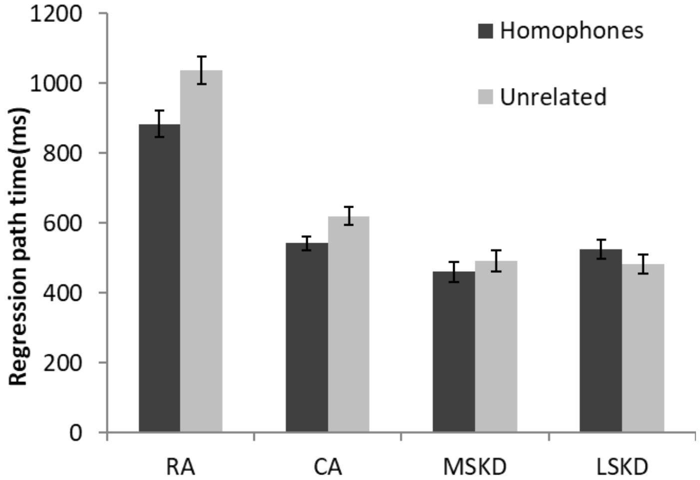
Figure 1. Gaze duration (panel a), regression path time (panel b), and total reading time (panel c), on homophone words and unrelated words, for each of the four participant groups.

Figure 1

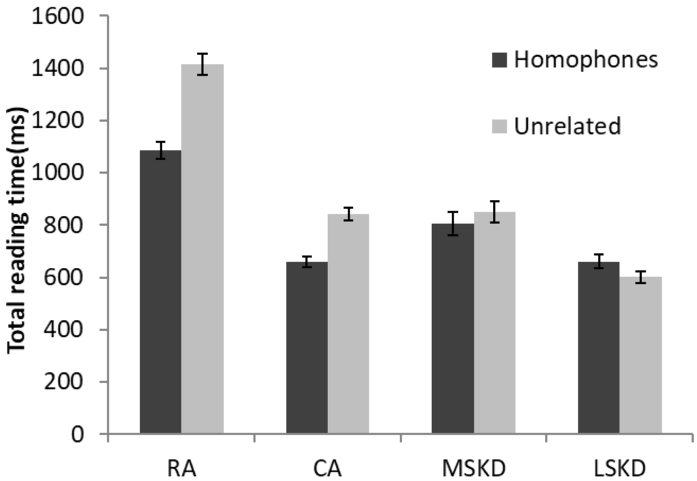
(a)


Homophones
Unrelated
Gaze duration(ms)
0
100
200
300
400
500
600
700
RA
CA
MSKD
LSKD

(b)


Homophones
Unrelated
Regression path time(ms)
0
200
400
600
800
1000
1200
RA
CA
MSKD
LSKD

(c)


Homophones
Unrelated
Total reading time(ms)
0
200
400
600
800
1000
1200
1400
1600
RA
CA
MSKD
LSKD