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

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1 **Phonological Coding during Sentence Reading in Chinese Deaf** 2 **Readers: An Eye-Tracking Study**

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

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

19 Word count: 5974

20 **Introduction**

21 Previous studies have found that many deaf individuals or hearing-impaired students
22 experience difficulty in learning to read, and the literacy development of average deaf
23 readers is delayed compared with their hearing peers (Kyle & Cain, 2015; Wauters, van
24 Bon, & Tellings, 2006). It is a significant achievement for deaf students to be able to
25 read at an age-appropriate level, but the majority fail to attain a level of literacy that
26 enables them to cope with the daily demands of modern society (Harris & Moreno,
27 2004). Investigating the cause of the reading difficulty in the deaf is thus very

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1 important. Moreover, attaining understanding of the nature of reading in the deaf would
2 be expected to contribute to theoretical models of reading (e.g. Mayberry, del Giudice,
3 & Lieberman, 2011).

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

9 For hearing readers, phonological coding is critical for high reading achievement
10 (Perfetti & Sandak, 2000). According to cognitive models of reading (Coltheart, Rastle,
11 Perry, Ziegler, & Langdon, 2001; Ziegler & Goswami, 2005), the route by which
12 readers access semantics may either be directly from orthography, or indirectly via
13 phonological mediation during reading. Regardless of which route is used for semantic
14 access, a number of studies have supported that phonological coding plays an important
15 role in the reading of hearing readers, even in logographic scripts like Chinese
16 (Grainger & Ferrand, 1994; Lee, Rayner, & Pollatsek, 1999; Lukatela, Frost, & Turvey,
17 1998; Tan & Perfetti, 1998). A four-year longitudinal study examined the relationship
18 between Chinese children's phonological skills and their success in reading (Ho &
19 Bryant, 1997). The results showed that prereading phonological skills strongly predicted
20 children's reading performance two to three years later.

21 However, the experimental findings of how phonological coding occurs among
22 deaf students have been controversial (Mayberry et al., 2011). One view suggests that
23 deaf readers could activate phonological coding during reading in the same way as
24 hearing readers (Musselman, 2000; Transler & Reitsma, 2005), and the difficulty of

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1 reading in deaf readers might be due to delayed reading development (Paul & Lee,
2 2010). An opposing view (to the delayed reading development view) is that deaf readers
3 have little reliance on phonological coding (Fariña, Duñabeitia, & Carreiras, 2017;
4 McQuarrie & Parrila, 2009; Perea, Marcet, & Vergara-Martinez, 2016), and instead
5 prefer to use different qualitative processes during reading (nonauditory channels, such
6 as visual lip reading, sign language; see Bélanger et al., 2012).

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

23 Importantly, the studies reported above that have employed isolated word
24 recognition tasks may not reflect on-line cognitive processing during natural reading,

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1 and as such any investigation of the roles of phonological skills in single word reading
2 cannot provide a full account of phonological processing in sentence or passage reading.
3 Little research to date has directly examined the phonological coding of deaf readers in
4 natural sentence reading (only three studies have investigated this in alphabetic
5 languages). Hanson, Goodell, and Perfetti (1991) used tongue twisters to test whether
6 deaf readers activated phonological coding in sentence reading. They found that both
7 deaf and hearing college students made more errors in their acceptability judgments on
8 tongue-twisters than they did on control sentences which indicated that deaf readers can
9 use phonological coding during reading.

10 Recently eye movement methodology has been adopted to investigate whether
11 deaf readers activate phonological coding during natural and silent sentence reading as
12 they read. The eye movement data are very informative as they allow us to understand
13 whether there are on-line processing differences between the deaf and hearing readers
14 during natural sentence reading. For example, Bélanger, Mayberry, and Rayner (2013)
15 used the boundary paradigm to explore adult deaf readers' processing of phonological
16 coding in parafoveal vision (the word next to the currently fixated word) during
17 sentence reading. They found no evidence for a parafoveal phonological preview
18 benefit in both skilled and less-skilled deaf readers, but hearing readers showed a
19 phonological preview benefit. In contrast, Blythe, Dickins, Kennedy, and Liversedge
20 (2018) adopted the same boundary paradigm and observed phonological coding from
21 parafoveal vision in deaf teenagers. In another study, Blythe et al. (2018) used the error
22 disruption paradigm to examine phonological coding from foveal vision (directly
23 fixated words) during sentence reading in the deaf teenagers. The results showed that

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1 deaf teenagers showed a pseudohomophone advantage, providing evidence for
2 phonological coding of fixated words during sentence reading in deaf teenagers.

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

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

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

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

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

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

1 Method**2 *Participants***

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

14 All participants in CA and RA controls had normal hearing. The CA controls
15 were aged from 13.42 to 20.8 years ($M = 16.86$ years, $SD = 2.14$) were matched to the
16 DS on chronological age ($t = -1.12$, $p > 0.05$). The RA controls were aged from 10.16 to
17 11.72 years ($M = 10.74$, $SD = 0.34$), and were matched to the DS on reading fluency,
18 reading comprehension and nonverbal IQ (see Table 1 for tests used and summary
19 scores). The reading fluency test requires readers to read and comprehend simple
20 sentences and to judge the contents as rapidly as possible within a three minute time
21 frame by ticking a box at the end of each sentence to indicate whether the information is
22 correct or incorrect (for example, ‘the sun rises in the west’; Pan et al., 2011; Lei et al.,
23 2011). The number of characters marked with correct sentences within 3 minutes is
24 calculated as the dependent variable. For reading comprehension, participants were

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1 asked to answer multiple choice questions or subjective questions after reading a short
 2 essay (Li, Wu, Zhou, Chen, & Nguyen, 2016). Raven's Standard Progressive Matrices
 3 were administered (Raven, Court, & Raven, 1996) to measure nonverbal IQ.

4 --TABLE 1--

5 *Material and Design*

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

18 --TABLE 2--

19 Rating Studies: A total of 40 fourth graders were invited to conduct two norming
 20 studies to ensure that the sentences were neutral. Firstly, the predictability of the targets
 21 was assessed based on sentence constraint ratings. Half of the participants were given
 22 the sentence context with a blank space in the location of the target word and were
 23 asked to fill in the word that best completed the sentence. The mean score of the

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1 sentences was 5% ($SD = 0.09$), indicating that all target words in the sentences were
2 low on predictability. Secondly, sentence difficulty was assessed on a five-point scale
3 (e.g., a score of “5” was “very difficult” to understand). Half of the participants were
4 presented with complete sentences with the correct target word and asked to rate each
5 one. The mean score of the sentences was 1.24 ($SD = 0.24$), indicating that all sentences
6 were appropriate given the reading level of the participants.

7 The experimental sentences had a length of 14 to 17 characters ($M = 15.15$, $SD =$
8 1.00). The target words consisted of two characters which never appeared among the
9 first four or the last four characters. Each sentence was presented only once to each
10 participant, with all of the conditions counterbalanced. Each participant read 45
11 sentences (15 per condition), which were randomly presented during the experiment.
12 The sentences used in the experiment are presented in full in Appendices 1.

13 *Apparatus*

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

20 *Procedure*

21 Participants were seated comfortably, and then a three-point horizontal calibration and
22 validation procedure was conducted. If the individual mean validation error or the error
23 for any one of the points was greater than 0.2° , then the procedure was repeated. The

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1 first nine trials were practice trials with three easy yes–no questions related to the
2 meaning of the sentences. Participants were presented with a single sentence at a time
3 and were instructed to read the sentences silently, and to press a button on the gamepad
4 once they had finished reading. On one-third of the trials, the sentence was followed by
5 a comprehension question, to which participants responded yes or no using a button on
6 the gamepad. Participants were informed that some of the words might be misspelled,
7 but they should simply do their best to understand the sentence. The overall
8 experimental session lasted for approximately 15 minutes.

9 *Data analysis*

10 Following convention (Bai, Yan, Liversedge, Zang, & Rayner, 2008), a data reduction
11 procedure combined short fixations (shorter than 40 ms) with nearby fixations, after
12 which fixations shorter than 80 ms or longer than 1200 ms were removed. Trials, in
13 which sentences received less than three fixations were deleted (affecting approximately
14 2.3 %), as well as trials, in which scores were more than three SD's from each
15 participant's mean (FFD:1.4%; GD: 1.8%; RP: 2.0%; TT: 1.2%). Similar to previous
16 studies in Chinese (e.g. Zhou et al., 2017), data analyses were performed within two-
17 character word regions for the target words.

18 Three early-stage processing and two late-stage processing eye movement
19 measures, defined according to Jared & O'Donnell (2017) and Friesen, Whitford,
20 Titone, & Jared (2020), were examined. Early-stage measures reflect early lexical
21 identification of a word, and include First Fixation Duration (FFD) which is the
22 duration of the first fixation on a word regardless of how many other fixations were
23 made, Gaze Duration (GD) which is the sum of all fixations on a word prior to moving
24 on to a different word, including refixations, and Regression out, which is the

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1 probability of regressing out of a word to an earlier word. Late-stage measures reflect
2 later integration processing of the sentences and later lexical identification, and include
3 Regression Path Time (RP) which is the sum of all fixation durations on a region from
4 first entering the region until going past that region, and Total Reading Time (TT)
5 which is the sum of all fixations on a word throughout the duration of the trial.
6 Although skipping rates were also examined, there were no significant differences
7 between the homophones and unrelated words ($b = 0.05$, $SE = 0.11$, $z = 0.42$); thus,
8 detailed analyses are not reported. Each measure is reported for the analyses of target
9 words in the sentences.

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

19 Analyses were performed with liner-mixed effects models (Bates, Maechler, &
20 Dai, 2009) within the R environment (R Development Core Team, 2012). For each
21 variable, fixed effects included Group and Word Type, and random effects included
22 random intercepts for participants and items, random slopes for Word Type across
23 participants, and random slopes for Word Type and Group across items. If the initial
24 model failed to converge then the random structure was incrementally trimmed,

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1 beginning with the items level. The model was run on log-transformed reading time.
2 Logistic generalized linear mixed models (GLMMs) were used for the regression data
3 and skip data. We report regression coefficients (b), standard errors (SE), and t values or
4 z values (t or $z = b/SE$). A two-tailed criterion ($|t|$ or $|z| \geq 1.96$) was used to determine
5 significance. The error disruption paradigm assumes that if readers activate the
6 meanings of words using phonological coding, then homophones should produce
7 shorter reading times compared to reading times on unrelated words. So, we mainly
8 focus on the differences in reading times (for all eye movement measures) between
9 homophones and unrelated words.

10 **Results**

11 *Deaf students compared with control groups*

12 Four participants from the DS, three from the RA controls, and one from the CA
13 controls were excluded from the data analysis because their response accuracy for
14 comprehension questions was below 70%. The accuracy of the comprehension
15 questions by the participants included in the analyses was 90% (RA controls), 89%
16 (DS) and 95% (CA controls). A one-way analysis of variance (ANOVA) showed that
17 the difference in reading accuracy of the three groups was significant [$F(2, 93) = 5.78$,
18 $p < 0.05$]. Post-hoc tests found that the RA controls had a significantly lower reading
19 accuracy than the CA students ($p < 0.05$), and the deaf students' reading accuracy was
20 lower than the CA controls ($p < 0.05$). In general, all three groups had high accuracy
21 demonstrating and understanding of the meaning of the sentences.

22 Means for each eye movement measure, broken down by participant group and
23 experimental condition are shown in Table 3. We ran the model with group (RA, DS,

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1 CA), and word type (correctly spelled words, homophones, unrelated words) as fixed
2 factors. The results of this model for the eye movement measures are shown in Table 4.

3 --TABLE 3--

4 --TABLE 4--

5 *Early-stage measures*

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

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

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1 *Late-stage measures*

2 A significant difference between homophones and unrelated words was observed in RP
3 and TT. Homophones were fixated for a shorter time than unrelated words. The group
4 (RA vs. DS) and word type (homophones vs. unrelated words) interaction was
5 significant in RP and TT. The group (DS vs. CA) and word type (homophones vs.
6 unrelated words) interaction was not significant in RP but was significant in TT. In RP,
7 for the CA controls and the DS, there was no significant homophone advantage (CA: b
8 $= -0.07$, $SE = 0.04$, $t = -1.61$; DS: $b = 0.00$, $SE = 0.04$, $t = 0.07$), for the RA controls,
9 there was a significant homophone advantage ($b = -0.20$, $SE = 0.05$, $t = -3.86$). In TT,
10 for the CA and the RA, there was a significant homophone advantage (CA: $b = -0.24$,
11 $SE = 0.04$, $t = -6.54$; RA: $b = -0.25$, $SE = 0.04$, $t = -6.52$), but for the DS, there was no
12 significant homophone advantage ($b = -0.02$, $SE = 0.04$, $t = -0.52$). In the group main
13 effects, the reading time of RA controls was significantly longer than the DS in RP and
14 TT. However, there was no significant difference between the DS and CA controls in
15 RP and TT.

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

22 The results clearly show that reading ability can impact upon performance in the
23 current experiment, and that the RA group had more regressions out, longer GD, longer
24 RP, and longer TT in comparison to the DS group. Additionally, the RA group showed

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1 a homophone advantage in the regression out, the RP, and the TT measures. However, it
2 should be noted that the deaf students in the current study had large individual
3 differences in reading ability, and these were not controlled for in the initial analyses of
4 the data. Therefore, reading ability within the DS group could be a factor that affects
5 whether phonological coding is activated during sentence reading in the deaf. For
6 example, previous studies have found that the use of phonological information is related
7 to the reading level of deaf readers (Perfetti & Sandak, 2000; Wang, Trezek, Luckner,
8 & Paul, 2008). Furthermore, Yan et al. (2015) have found that more-skilled Chinese
9 deaf readers show a phonological preview benefit compared to less-skilled Chinese deaf
10 readers (the test of classification was reading fluency). In order to examine whether
11 Chinese deaf students' individual differences in reading level are related to the use of
12 phonological coding, we divided the deaf students in the current study into more-skilled
13 and less-skilled readers, according to reading fluency (the fluency test needed
14 participants to make a value judgment following each sentence, and hence this test also
15 includes comprehension).

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

17 In line with a previous study (Häikiö, Bertram, Hyönä, & Niemi, 2009), we used a
18 median split procedure to categorize the deaf student participants into two subgroups,
19 based on their silent-reading fluency score. The median (score = 310.67) is the standard
20 cut off point for characterising readers as being more-skilled or less-skilled. Using that
21 criteria we divided the sample of deaf students into less-skilled (LSKD) and more-
22 skilled (MSKD) students, and the reading fluency of these two subgroups was
23 significantly different ($t = -7.36, p < 0.001$), the reading comprehension was
24 significantly different ($t = -3.06, p < 0.05$), but the IQ and age of these two subgroups

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1 was not significantly different (IQ: $t = -0.24, p > 0.05$; age: $t = 0.84, p > 0.05$). Means
2 for each dependent measure, broken down by participant group and experimental
3 condition, are shown in Table 5. We then ran a linear mixed-effects model with group
4 (MSKD vs. LSKD), and word type (homophone vs. unrelated) as fixed factors. The
5 results of this model for the eye movement measures are shown in Table 6.

6 --TABLE 5--

7 --TABLE 6--

8 *Early-stage measures*

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

15 *Late-stage measures*

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

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1 homophones produced significantly shorter total reading time than unrelated words.
2 These data indicated that both chronologically age matched, and reading ability
3 matched groups showed a homophone advantage. There was no evidence of a
4 homophone advantage in the deaf students. However, when the deaf students were
5 divided into more-skilled and less-skilled students, the homophone advantage was
6 observed for the more-skilled deaf students, and this advantage was absent in the less-
7 skilled deaf students. Overall, our analysis of the data for the two subgroups of deaf
8 students (more-skilled and less-skilled) provide evidence to suggest that more-skilled
9 deaf students use phonological coding during sentence reading, whereas less-skilled
10 deaf students do not.

11 This study found significant differences between homophones and unrelated
12 words in the later eye movement measures (total reading time) for hearing control
13 groups, and the total reading time on homophones was remarkably shorter than those
14 for unrelated words. This indicates that phonological coding occurs at the later lexical
15 identification stage in typical students reading Chinese sentences. However, we also
16 found the RA controls showed a homophone advantage in the regression out and the
17 regression path time measures, whereas the CA controls did not. We interpret this
18 finding to indicate that phonological information may play an important role in the
19 integration process of sentences for the CA controls. However, the RA controls who
20 were much younger hearing students showed a homophone advantage for both early and
21 later lexical identification measures. These time course differences in the control groups
22 may simply be related to age, since Chinese readers who are at the early stages of
23 learning to read, are taught using hanyu pinyin (Yan, Miller, Li, & Shu,2008) and have

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1 been proposed to rely on phonological mediation, unlike skilled readers who have been
2 shown to have more direct access to semantics from orthography (Zhou et al., 2017).

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

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

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1 deaf readers. This is not the case for the RA controls in this study, since both more
2 skilled and less skilled readers in that group showed a homophone advantage (see
3 Appendices 3). Therefore, it is not reading ability per se that prevents the use of
4 phonological coding in the less skilled deaf readers in this study.

5 Since the more skilled deaf readers showed the same effects for the homophones
6 as the control groups, we can infer that they have made use of phonological coding
7 during reading sentences in this experiment. However, the less skilled deaf readers did
8 not show the homophone advantage, indicating that they were unable to use
9 phonological coding when they read the sentences. An obvious question relates to why
10 less skilled deaf readers are unable to activate phonological coding during sentence
11 reading. Morford, Kroll, Piñar, and Wilkinson (2014), Meade, Midgley, Sehyr,
12 Holcomb, and Emmorey (2017) found that deaf readers who were less skilled in their
13 English were more likely to use sign translations. It could therefore be the case that the
14 less skilled deaf readers rely on sign phonology during reading, and the more skilled
15 deaf readers rely on sound phonology. The reason that there are shorter reading times
16 and regressions for homophones, compared to unrelated words, is that the homophones
17 share the same sound phonology as the correctly spelled words. The literature suggests
18 that deaf readers do engage in sign phonology during reading (Bélanger, Morford, &
19 Rayner, 2013; Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Ormel, Hermans,
20 Knoors, & Verhoeven, 2012; Pan, Shu, Wang, & Yan, 2015; Treiman & Hirsh-Pasek,
21 1983). However, it is not known whether deaf readers who engage in sign phonology
22 during reading are less skilled deaf readers. What is known is that if readers are using
23 sign phonology, then one would not expect to see the homophone advantage during
24 reading, as there is no equivalent sign phonology for written homophones. Specifically,

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1 sign phonology includes four formational parameters: handshape, location, movement,
2 and orientation (Battison, 1978; Stokoe, Croneberg, & Casterline, 1965), and sign-
3 phonological relatedness has been defined as sharing at least two formational
4 parameters (Ormel et al., 2012). In the present study, the sign phonology of target
5 characters in the sentences do not share any two sign formational parameters. This
6 means that, in the current study, there is no equivalent sign phonology for the written
7 homophones.

8 A further question that arises from the findings in the present study relates to
9 what underpins whether a deaf person becomes a more skilled or a less skilled reader.
10 According to Musselman (2000), if the reading processing of the more-skilled deaf
11 reader is similar to that of hearing readers, we can speculate that the reason for
12 difficulty in reading in that group is due to a delay in their reading development, caused
13 by hearing loss. However, if the reading processing of the less-skilled deaf reader is
14 different to that of hearing readers, and, if that group relies more on sign language
15 representation in the reading process (see Bélanger et al., 2012; Sterne & Goswami,
16 2000), then we can infer that the reason for difficulty in reading in the less skilled
17 readers may reflect atypical (rather than delayed) reading development.

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

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1 develop and build the connections between the written language forms and sign
2 language.

3 **Conclusion**

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

12 **Acknowledgement**

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15 **Ethics approval**

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

20 **Conflict of interest**

21 The authors declare no conflict of interest.

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

3 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 是什么样子的了。	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 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

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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

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Scientific Studies of Reading

Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS****1 Appendices 2**

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

3 *Early-stage measures***4 *Correctly spelled words vs. homophones***

5 Correctly spelled words were fixated shorter than homophones in FFD ($b = 0.07$, $SE =$
6 0.02 , $t = 4.77$), and GD ($b = 0.21$, $SE = 0.02$, $t = 9.42$). The interactions between group
7 (RA vs. DS) and word type were not significant in FFD ($b = -0.06$, $SE = 0.04$, $t = -1.69$),
8 however, in GD were significant ($b = -0.17$, $SE = 0.05$, $t = -3.08$). The interactions
9 between group (DS vs. CA) and word type were significant in FFD ($b = 0.08$, $SE =$
10 0.04 , $t = 2.02$), and GD ($b = 0.13$, $SE = 0.06$, $t = 2.35$). In regression out, there was no
11 significant difference between correctly spelled words and homophones ($b = 0.20$, $SE =$
12 0.11 , $z = 0.07$). The interactions between group and word type were not significant ($|z| <$
13 0.75).

14 *Correctly spelled words vs. unrelated words*

15 Correctly spelled words were fixated shorter than unrelated words in FFD ($b = -0.06$, SE
16 $= 0.02$, $t = -3.80$), and GD ($b = -0.22$, $SE = 0.02$, $t = -9.91$). The interactions between
17 group (RA vs. DS) and word type were not significant in FFD ($b = 0.03$, $SE = 0.04$, $t =$
18 0.84), however, in GD were significant ($b = 0.21$, $SE = 0.05$, $t = 3.89$). The interactions
19 between group (DS vs. CA) and word type were not significant in FFD ($b = 0.04$, $SE =$
20 0.04 , $t = 1.07$), however, in GD were significant ($b = 0.12$, $SE = 0.06$, $t = 2.12$). In
21 regression out, correctly spelled words produced less regression out than unrelated
22 words ($b = 0.52$, $SE = 0.11$, $z = 4.74$). The interactions between group (RA vs. DS) and
23 word type were significant ($b = 0.63$, $SE = 0.28$, $z = 2.27$), however, the interactions

Scientific Studies of Reading

Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS**

1 between group (DS vs. CA) and word type were not significant ($b = -0.54$, $SE = 0.29$, z
2 $= -1.86$).

3 ***Late-stage measures***

4 ***Correctly spelled words vs. homophones***

5 Correctly spelled words were fixated shorter than homophones in RP ($b = 0.27$, $SE =$
6 0.03 , $t = 9.89$), and TT ($b = 0.42$, $SE = 0.03$, $t = 15.20$). The interactions between group
7 and word type were significant in RP ($|t| > 3.16$), and TT ($|t| > 2.06$).

8 ***Correctly spelled words vs. unrelated words***

9 Correctly spelled words were fixated shorter than unrelated words in RP ($b = -0.35$, SE
10 $= 0.03$, $t = -12.79$), and TT ($b = -0.59$, $SE = 0.02$, $t = -26.55$). The interactions between
11 group and word type were significant in RP ($|t| > 4.21$), and TT ($|t| > 6.40$).

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1 Appendices 3

2 In this section, we document results for the more-skilled and less-skilled RA group. We
3 divided the RA group into more-skilled and less-skilled readers in terms of their reading
4 fluency. We then ran a linear mixed-effects model with group (MSKD vs. LSKD), and
5 word type (homophone vs. unrelated) as fixed factors. The results showed that the
6 interactions between group and word type were not significant in FFD ($b = 0.09$, $SE =$
7 0.06 , $t = 1.45$), GD ($b = 0.08$, $SE = 0.09$, $t = 0.82$), regression out ($b = 0.47$, $SE = 0.33$, z
8 $= 1.43$), RP ($b = 0.17$, $SE = 0.11$, $t = 1.61$), and TT ($b = 0.06$, $SE = 0.08$, $t = 0.79$).

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Scientific Studies of Reading

Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS****Table 1**

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

	RA	DS	MSKD	LSKD	<i>t</i>
	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	
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.

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Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS****Table 2**

Character properties of the three experimental conditions

	Correctly spelled <i>M (SD)</i>	Homophone <i>M (SD)</i>	Unrelated <i>M (SD)</i>
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.

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Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS****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.

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Scientific Studies of Reading

Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS****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		
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>z</i>	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>t</i>
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.

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Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS****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

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Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS****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		
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>z</i>	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>t</i>
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.

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1 **Figure Captions**

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

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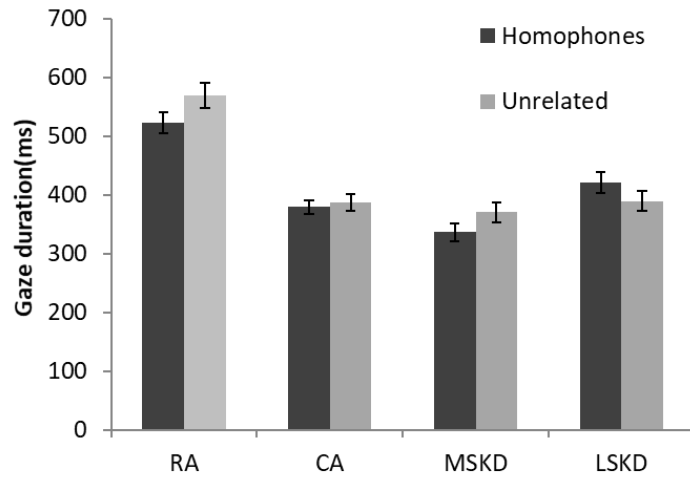
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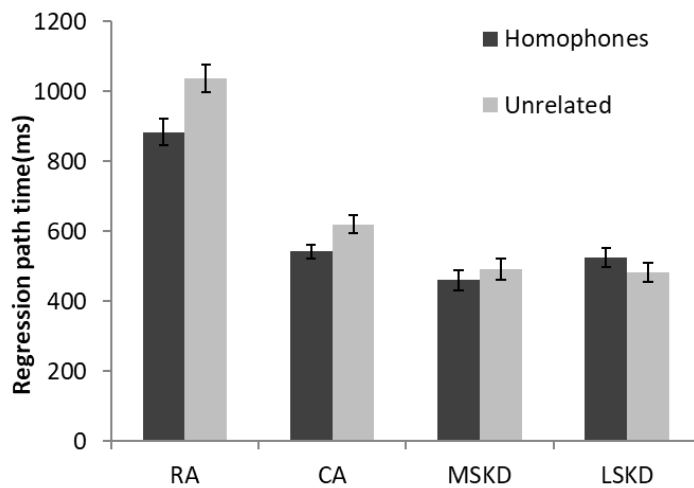
Running head: **PHONOLOGICAL CODING IN CHINESE DEAF READERS**1 **Figure 1**

2 (a)



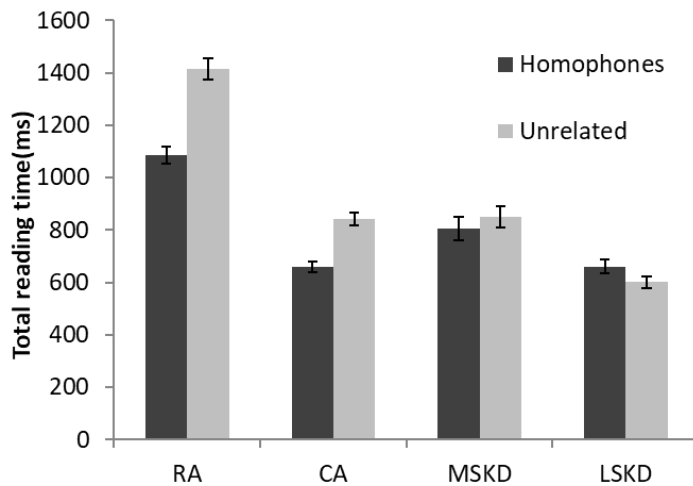
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4 (b)



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6 (c)



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