

Phonological activation in Hong Kong deaf readers:
Evidence from eye movements and event-related
potentials

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Abstract

Understanding the roles of spoken and sign phonological code in reading processes is important for educators of deaf and hard-of-hearing students. However, the pool of data on this topic is limited and has mostly centered on readers of alphabetic languages. In places like Hong Kong, where deaf signers are relatively few, the shortage of research on phonological processing during reading is even more severe. This thesis addressed this problem by investigating the cognitive processes underlying Chinese reading in Hong Kong deaf readers using two methodological approaches, eye movements and event-related potentials, across four separate studies.

Studies 1 and 2 used the error disruption paradigm with eye-tracking to investigate the patterns of orthographic and phonological activation in hearing and deaf readers. The hearing reader data suggested that they rely mostly on orthography to access word meanings in early processing. However, early phonological activation was found to be facilitated top-down by semantics when targets were predictable. The deaf readers were also found to rely primarily on orthographic information to access word meanings, but phonological code played a role in late processing and was modulated by contextual predictability and reading level.

Study 3 used a parafoveal preview paradigm with eye-tracking to investigate how sign phonologically related previews affect reading processes in Hong Kong deaf readers. The pattern of results suggested that these readers activate sign phonological representations when reading Chinese words and that different sign phonological parameters (i.e., handshape, location, and movement) have different effects on parafoveal processing.

Study 4 investigated orthographic, spoken phonological, and sign phonological processing in Hong Kong deaf readers using two error disruption paradigms with ERPs, focusing on the P200 and N400 components. The results for Experiment 1 revealed that N400 amplitudes were reduced in the orthographic condition, which suggested that orthographic representations were facilitating lexical access. In the homophonic condition, N400 amplitudes were increased in the right central elec-

trodes. In Experiment 2, P200 amplitudes were significantly reduced in the left anterior electrodes in the sign phonological condition. In sum, the results of Experiment 1 and Experiment 2 suggest that the early P200 component is modulated by sign phonology, and the later N400 component is modulated by orthography and spoken phonology in Hong Kong deaf readers.

In sum, these studies suggest that while deaf readers tend to activate word meanings directly through orthography, they can also activate spoken phonological and sign phonological codes. Consistently across the eye movement and ERP studies, the effects of sign phonological activation emerged in early stages of processing, and the effects of spoken phonology emerged in later stages of processing. The different time courses of spoken and sign phonological activation may be an indication that deaf readers tend to use sign representations to activate word meanings and spoken phonological representations for later integrative processes. In conclusion, these findings can be taken to suggest that both types of phonological code are important for deaf readers.

Declaration

I, Philip Thierfelder, declare that this thesis, titled *Phonological activation in Hong Kong deaf readers: Evidence from eye movements and event-related potentials*, and the work presented in it are my own. I confirm that:

- The thesis comprises only my original work towards the Doctor of Philosophy except where indicated in the preface;
- due acknowledgement has been made in the text to all other material used; and
- the thesis is fewer than the maximum word limit in length, exclusive of tables, maps, bibliographies and appendices as approved by the Research Higher Degrees Committee.

Signed: Philip Thierfelder

Date: 7/27/2020

Dedication

*This thesis is dedicated to Mom and Dad, whose love, encouragement, and support have
gotten me through my doctoral journey.
I miss you, Dad.*

Preface

This thesis is a *thesis with publication* and has been written in accordance with University of Melbourne guidelines.

Chapters 2–4 each consist of a research paper that has been published in a peer-reviewed academic journal. For each of these, I was the first author and my work contribution was greater than 50%.

The first paper, presented in Chapter 2, was authored by myself, Gautier Durantin, and Gillian Wigglesworth. For this paper, I was responsible for conceptualization, carrying out data collection and analysis, writing the original draft, and revising and editing. Gautier Durantin produced the scripts for pre-processing the pupillary response data and provided feedback on the first draft. Gillian Wigglesworth acquired the funding for this project and provided feedback on project conceptualization and on the first draft.

Chapter 2 publication information: Thierfelder, P., Durantin, G., & Wigglesworth, G. (2020). The effect of word predictability on phonological activation in Cantonese reading: A study of eye-fixations and pupillary response. *Journal of Psycholinguistic Research*. <https://doi.org/10.1007/s10936-020-09713-8>

The papers presented in Chapters 3 and 4 were authored by myself, Gillian Wigglesworth, and Gladys Tang. For these papers, I was responsible for conceptualization, carrying out data collection and analysis, writing the original draft, and revising and editing. Gillian Wigglesworth acquired the funding for both studies and provided feedback on project conceptualization and on the first draft. Gladys Tang provided feedback on experimental methodology and the first draft.

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Chapter 5, titled *The time course of Cantonese and Hong Kong Sign Language phonological activation: An ERP study of deaf bimodal bilingual readers of Chinese*, is a single-author paper which has been submitted for peer review.

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Finally, I would like to give a special thanks to all the participants, as well as the deaf community of Hong Kong, without whom this research would not have been possible.

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Chapter 1

Introduction

1.1 Introduction and background

Reading instruction in educational programs for deaf and hard-of-hearing (DHH) students has had limited success in helping students achieve high rates of literacy, such that many graduate high school with reading levels lower than those of their hearing peers (Kelly & Barac-Cikoja, 2007; Mayberry et al., 2011). To ameliorate this problem of unequal educational achievement, researchers have suggested that we must better understand the unique cognitive and linguistic characteristics of DHH students (Marschark et al., 2011) and the factors that distinguish skilled and less-skilled DHH readers (Bélanger, Baum, et al., 2012; Chamberlain & Mayberry, 2008).

As deficits related to phonological coding have often been hypothesized to be a cause of reading difficulties in deaf readers (Paul et al., 2009; C. A. Perfetti & Sandak, 2000; Y. Wang et al., 2008), researchers have been particularly interested in this aspect of deaf cognition. Investigations into deaf reading processes have led to considerable progress in this area, and researchers have begun to understand some of the unique characteristics of deaf readers and how they use phonological code. For example, bimodal bilingual deaf readers, who know both a written language and a sign language, have been shown to automatically activate mental representations of the word's sign translation when recog-

nizing its written form (Chiu et al., 2016; Chiu & Wu, 2016; Kubus et al., 2015; Morford et al., 2019; Morford et al., 2011; Pan et al., 2015), a process which has been shown to possibly engage the brain’s sensorimotor system (Quandt & Kubicek, 2018). Furthermore, despite having limited access to the spoken phonological system, deaf readers have also been shown to activate spoken-language-based phonological code during silent reading (Gutierrez-Sigut et al., 2017; Hanson & Lichtenstein, 1990; Y. Li et al., 2014; M. Yan et al., 2015). There has also been evidence that some deaf readers might be activating units of phonological code based on mouth shapes acquired through lipreading, rather than phonological units based on acoustic information (Elliott et al., 2012). However, as deaf reading is still relatively understudied, more research is needed to determine whether these findings can be replicated with deaf bimodal bilinguals of different backgrounds.

This thesis aims to investigate the role of phonological code in the cognitive processes that underlie silent reading and focuses on a group that has not often been examined in past research: Hong Kong deaf readers. Currently, the majority of research on deaf reading processes has focused on readers of languages that are written in alphabetic scripts—most prominently, English. Some studies have focused on deaf readers of Chinese from mainland China and Taiwan. However, communication background has been shown to influence how deaf readers use phonological code during reading (Koo et al., 2008), and Hong Kong deaf readers are quite different from those in mainland China and Taiwan in this respect.

Before continuing with the discussion of Hong Kong deaf readers, it is important to have some familiarity with the unique sociolinguistic situation of Hong Kong. The primary spoken language in Hong Kong is Cantonese, used as a first language by around 89.5% of the population (Department, 2011). The official written language of Hong Kong, Modern Standard Chinese, is based on spoken Mandarin (or *Putonghua*), the official language of mainland China, rather than Cantonese. While Cantonese is often referred to as a “dialect” of Chinese, it differs considerably in pronunciation, lexicon, and grammar, to such an extent that it is largely unintelligible to monolingual speakers of Mandarin. Can-

tonese can be written using a set of Cantonese-specific Chinese characters, but these are not taught in schools and their use is limited to informal personal communications and certain publications written in a colloquial style (Matthews & Yip, 2013). In addition to Cantonese, English and Mandarin also occupy important positions in Hong Kong society. English has long held high status in Hong Kong due to Hong Kong's history as a British Colony up to 1997, and Mandarin has also become an increasingly important language for conducting business with mainland China. Currently, the Hong Kong government promotes *biliteracy and trilingualism*, with the goal of training Hong Kongers to be bilit-erate (in written Modern Standard Chinese and English) and trilingual (in Cantonese, Mandarin, and English). In the educational setting, there is no agreed-upon model for achieving this, and language education models differ greatly across schools (L. Wang & Kirkpatrick, 2015).

Due to the unique situation just described, Hong Kong deaf readers are already unique in that the form of Chinese they learn to read and write, Modern Standard Chinese, is different from the primary spoken language used in day-to-day life in their community. Furthermore, Hong Kong deaf readers do not learn a Chinese romanization system (e.g., Hanyu Pinyin, Zhuyin-Fuhao, etc.) in their Chinese reading classes, as this has not traditionally been part of the Hong Kong curriculum as it is in other places like mainland China and Taiwan (C. S.-H. Ho & Bryant, 1997b). Another unique aspect of the Hong Kong deaf community relates to their acquisition of sign language. Teachers in many deaf schools in mainland China and Taiwan use a variety of Signed Chinese in the classroom. Signed Chinese refers to any of the artificial sign systems based on spoken Mandarin, which include numerous invented signs for words that exist in spoken Mandarin and written Chinese but not in the natural sign language (Lee et al., 2001; Lytle et al., 2006). However, most Hong Kong deaf people have been educated orally and learn Hong Kong Sign Language (HKSL) from their peers (Sze et al., 2013), although limited use of signed Chinese has been observed in classroom communication (Tang et al., 2015). Because most Hong Kong deaf readers learn to read Chinese without the aid of a romanization

system or sign language in school, it is possible that they will exhibit different patterns of sign and spoken phonological activation than has been found in past studies of different populations of deaf readers of Chinese (e.g., Chiu et al., 2016, Chiu & Wu, 2016, P. Li et al., 2017, Y. Li et al., 2014, Pan et al., 2015, M. Yan et al., 2015). Of particular relevance to the current thesis are three eye-tracking studies—M. Yan et al., 2015, which examined spoken phonological activation and is discussed in Chapter 3, as well as Chiu and Wu (2016), Pan et al. (2015), which focused on sign phonological activation and are discussed in Chapter 4.

1.1.1 Phonological coding and awareness

Some researchers have proposed that the difficulties many deaf readers face in achieving high levels of literacy may be due to deficits in their spoken phonological coding and awareness (PCA) skills (Paul et al., 2009; C. A. Perfetti & Sandak, 2000; Y. Wang et al., 2008). Phonological coding refers to readers' knowledge of the connection between the orthographic units of the written language with the sound-based phonological units of the spoken language. In the case of deaf readers, sound-based phonological units might be substituted with other means of sensory-based codes such as visual phonemes (i.e., *visemes*) acquired through speech reading (Elliott et al., 2012), visual phonics (Narr, 2008) or cued speech (LaSasso et al., 2003). Phonological awareness, in contrast, refers to a speaker's knowledge of the phonological system of their language, irrespective of their knowledge of orthographic forms (Mayberry et al., 2011). Some studies in the literature on PCA refer to *phonemic awareness*, which is the ability to use knowledge of the phonological system in tasks such as sound segmentation (dividing words into separate sounds) and blending (combining different sounds sequentially; Luetke-Stahlman & Nielsen, 2003).

There is debate around the issue of how much emphasis should be given to the teaching of PCA skills in deaf education. Some researchers have argued that phonological coding skills are of central importance for deaf literacy development (Paul et al., 2009; C. A.

Perfetti & Sandak, 2000; Y. Wang et al., 2008), while others have argued that they are of less primary importance (Allen et al., 2009; Bélanger, Baum, et al., 2012; Bélanger et al., 2013). This issue is important as educators’ beliefs surrounding this issue can have implications for classroom instruction. Luckner and Handley (2008), for instance, point out that some educators neglect the teaching of PCA skills on the assumption that phonology is of minor importance to literacy acquisition in deaf children. Conversely, among teachers who believe that strong phonological skills are of central importance, another risk exists, wherein an overfocus on teaching phonological skills can come at the expense of other important aspects of reading instruction (Allen et al., 2009).

Some insight into this issue has been revealed by meta-analyses of studies on phonological coding skills in relation to reading achievement. One meta-analysis of studies investigating the effects of phonological awareness training on reading development in hearing children, by Bus and van IJzendoorn (1999), determined that PCA skills accounted for 12% of the variance in word identification skills. The authors concluded that PCA skills were “an important but not sufficient condition for learning to read” (Bus & van IJzendoorn, 1999, p. 413), with other conditions such as parents’ early storybook reading and vocabulary knowledge being important predictors as well. Furthermore, they concluded that phonological training, especially when paired with orthographic training, can lead to improvements in children’s PCA skills and, subsequently, their reading skills. Mayberry et al. (2011) carried out a meta-analysis of 57 studies looking at the relationship between PCA and reading skills among deaf people. The studies included in the analysis used a variety of different tasks intended to isolate PCA skills, including lexical decision making, rhyming, and phoneme manipulation. The meta-analysis revealed that, overall, PCA skills predicted 11% of the variation found in deaf participants’ reading proficiency, which was similar to the degree of variance predictable based on other factors such as speech intelligibility, speech reading, nonverbal IQ, memory span, and orthographic knowledge. However, 35% of the variance in reading ability could be predicted by overall language ability—that is, the participants’ skill in spoken or signed language.

Researchers have not yet reached a consensus regarding whether PCA skills, accounting for 11% of the variance in reading skill among deaf readers, justify conferring a central role to PCA skills development in early literacy education (see Allen et al., 2009, Paul et al., 2009, Y. Wang et al., 2008). However, it is important to note that these meta-analyses suggest that PCA skills are of similar significance for both populations. Paul et al. (2009) argued that the PCA skills for both hearing and deaf children should be looked at in similar terms—as being important, but not solely sufficient, for the development of proficient reading skills.

1.1.2 The Chinese writing system

The meta-analyses discussed above focused primarily on research on English. Chinese, however, is a vastly different writing system from English and other alphabetic scripts, so it cannot be assumed that findings from studies on English reading can be generalized to Chinese. The next section will review some key literature on Chinese reading development. However, before doing so, some of the distinguishing features of Chinese script that may impact on how Chinese readers acquire literacy will be reviewed.

Chinese characters have three layers of orthographic structure. The first layer consists of strokes (e.g., 丶, 一, |), which contain no phonological or semantic information. Logographemes comprise the second layer of orthographic structure. As an example, the character 估 /gu2/ [estimate] consists three logographemes: 亻, 十, and 口. While 249 logographemes have been identified in Chinese, only 84 of these can stand alone as independent characters (Lui et al., 2010). For example, 十 /sap6/ [ten] and 口 /hau2/ [mouth] are meaningful characters in themselves, while 亻 only exists as a semantic component of other characters. The third layer of orthographic structure consists of semantic and phonetic radicals, which contain information related to the meaning and pronunciation of the character. There is a degree of overlap between the logographemic and radical layers. The previous example 估 /gu2/, for instance, consists of the semantic radical 亻 [person] and the phonetic radical 古 /gu2/ [ancient]. However, the information

conveyed by radicals such as these is generally unreliable. It is estimated that only 26% of Chinese characters have a Mandarin Chinese pronunciation that corresponds to their phonetic radicals (this figure would be lower for Cantonese, which has more base syllables), and 14% to 46% have meanings that are clearly related to their semantic radical (Gao et al., 1993). As an example of a character with unreliable semantic and phonological information, the character 猜 /caai1/ [guess] consists of the semantic radical 犳 [dog] and the phonetic radical 青 /ceng1/, neither of which gives useful information regarding the character’s meaning or pronunciation.

Chinese differs from alphabetic languages in how it maps phonetic information onto individual characters. In English, the pronunciations of unfamiliar words can be assembled one letter at a time using a successive procedure of grapheme to phoneme mapping. For example, *wug* can be divided into /w/, /ʌ/, and /g/. In contrast, Chinese phonetic radicals, such as 古 /gu2/ in 估 /gu2/, can only map to whole syllable—that is, nothing contained within it corresponds to /g/, /u/, or the second tone. Given the unreliable nature of phonetic radicals, it is difficult for readers to guess the pronunciations of unfamiliar characters correctly.

Finally, homophonic characters are highly prevalent in Chinese. In Cantonese, there is an average of approximately 17 homophonic characters per base syllable and a total of 625 phonologically distinct base syllables (1761 with tones; LSHK, 1997). The characters 同 [same], 童 [child], 瞳 [pupil (eye)], and 銅 [copper], for example, all share the pronunciation /tung4/. The high prevalence of homophones in Chinese might influence how Chinese readers utilize phonological information. For example, Feng et al. (2001) argued that, compared to English readers, Chinese readers rely more on orthography because phonological information is less useful for distinguishing words.

1.1.3 Chinese reading development

In the previous section, some notable features of Chinese script were described. One of these was that Chinese characters do not contain reliable phonetic information or any

components that equate to phonemes as letters do in alphabetic languages. Because of this, a common view has existed that, unlike English, phonology plays little or no role in Chinese reading (see Hoosain, 1991). However, research has shown that, in fact, the development of reading skills in Chinese, like English, also involves phonological coding, though reading development in the two languages also differs in certain respects.

Hearing readers

A study of Hong Kong and Taiwanese Chinese-speaking and British English-speaking children, all between 8 and 9 years old, by Huang and Hanley (1995), looked at the relationship between phonological awareness, visual skills, and reading ability. Visual skills were measured by two visual acuity tests. One task, for example, required subjects to learn colors associated with six different abstract line-drawings, and then, when later presented with the line-drawings again, point to their associated colors. The phonological awareness test involved phoneme difference tasks in which participants would listen to a group of words (in Chinese or English) and choose the one that was different from the rest in terms of one of its component sounds. For example, among the Mandarin words *ba*, *bo*, *fei*, and *bai*, *fei* is the correct choice because it differs in its first phoneme. The second test was a phoneme deletion test in which subjects were required to pronounce a word according to how it would sound if a specific phoneme was deleted. For example, the experimenter might say the word *ku* and ask the subject to say it without the first sound (correct answer: *u*). Chinese reading ability was measured by a Chinese character recognition test in which subjects were asked to read aloud from a list of characters ordered in increasing difficulty, while the English reading test required subjects to read 100 words aloud from a list. This study found that phonological skills, but not visual skills, related significantly to British children's English reading ability. On the other hand, while visual skills were found to be of primary importance for the Chinese reading children, phonological awareness was also found to correlate with reading skill.

In another cross-cultural comparative study, McBride-Chang et al. (2005) investi-

gated the relationship between phonological and morphological structure awareness with word recognition skills in second-grade readers from Beijing, Hong Kong, Korea, and the United States. Phonological awareness was tested with phoneme and syllable deletion tasks. In the morphological structure awareness task, children listened to orally presented stories and then were asked to construct new compound words based on information they were given in the stories. They found that across all four groups, both phonological and morphological structure awareness correlated with word knowledge, but they also found that phonological awareness was more important for readers of English and Korean than for readers of Chinese. In contrast, morphological structure awareness was more important for Chinese and Korean readers than English readers.

H. Li et al. (2012), in a study examining the role of visuo-orthographic, phonological, and morphological skills in character recognition among kindergarten and primary school students in Beijing, also found a very early role of visual skills among kindergarteners, though not in primary school students. Among primary school students, orthographic skills, however, were found to be more critical for literacy development. Phonological skills were important among both kindergarten and primary school students.

There has been some evidence that phonological awareness becomes more important for Chinese readers as reading skill develops. Looking at the development of Chinese reading skills across grade levels in Beijing children, Siok and Fletcher (2001) found that while visual skills predicted reading success at lower grade levels (Grade 1), phonological awareness was related to reading ability in later grades (Grades 2, 3, and 5). This shift from reliance on visual to phonological skills is a pattern that has also been found in Hong Kong students, who progress from a phase of relying on logographemes in character identification to relying more on phonetic radicals (C. S.-H. Ho & Bryant, 1997a, 1997c).

Deaf readers

Phonological skills also seem to be important for Chinese reading development in DHH students. In a developmental study by Cheung et al. (2013), the effects of auditory

discrimination on reading development and the use of orthographic and phonological codes in Chinese character reading were examined. Participants included 34 Hong Kong DHH (hearing threshold above 70 dB) students of different reading levels. Based on the results of a graded Chinese character naming test, 10 participants had a Grade 1 reading level (participant ages: 11–18.83 years old), 12 had a Grade 2 reading level (ages: 11.08–19.17), and 12 had a Grade 6 reading level (ages: 11.67–18). The study also included a hearing control group that was matched for age and reading level. In the first experiment, participants had their auditory discrimination ability assessed based on an auditory discrimination task in which they had to listen to syllable pairs and judge whether they were rhyming pairs or homophones. Results showed a significant correlation between auditory discrimination ability and reading ability. Furthermore, their analysis supported the claim that poor auditory discrimination is a causal factor leading to weaker reading skills.

Cheung et al.'s (2013) second experiment was a synonym decision task where participants were presented with a stimulus character (e.g., 睹 /dou2/ [see]) and had to choose the synonym (e.g., 見 /gin3/ [see]) among four distractor characters: an orthographic distractor sharing a logographeme with the stimulus (e.g., 煮 /zyu2/ [cook]), another orthographic distractor sharing a semantic radical with the stimulus (e.g., 眠 /min4/ [sleep]), a homophone (e.g., 島 /dou2/ [island]), and character that rhymed with the stimulus (e.g., 土 /tou2/ [soil]). DHH students at the Grade 1 and Grade 2 reading levels chose fewer phonological distractors than hearing controls, showing a greater reliance on orthographic over phonological information. The DHH students' greater reliance on orthographic information, however, diminished by the Grade 2 reading level (at which point, their task performance was similar to their hearing peers). The DHH students' tendency to choose orthographic distractors was lower among those with higher reading levels. The authors also found that readers at the Grade 2 level, in comparison to Grade 1 readers, had significantly better auditory discrimination skills and a greater tendency to choose phonological distractors, indicating that the preference for orthographic

information reduces as phonological code become available.

From these developmental studies, it is clear that phonological coding and awareness skills correlate with word recognition skills in both hearing and deaf readers of Chinese. Visual skills are of particular importance during an early, initial stage of literacy acquisition, but this pattern shifts such that reading skill levels in later grades are more closely related to orthographic and phonological skills.

1.1.4 Cognitive models of reading

The studies on PCA skills in relation to reading achievement and development suggest that phonological code does play a role in reading. However, knowing this does not tell us anything about whether or how that phonological code is being used by readers to understand text. To answer these questions, some researchers have focused on uncovering the cognitive processes that underlie silent reading. Decades of research into this issue have produced different models that aim to capture how word meanings are activated from orthography. An early, influential model, the activation-verification model (Van Orden, 1987), posited that as we read a word a mental representation of its phonological form is immediately activated, which then, in turn, activates the word's semantic representation (i.e., its meaning).

The connectionist model (Seidenberg & McClelland, 1989) posits that both the direct (orthography to meaning) and indirect (orthography to phonology to meaning) routes are always activated simultaneously during reading. However, the phonological code generated by the indirect route is not always utilized to access meaning. Harm and Seidenberg (2004) further developed this model by investigating the divisions of labor between the two routes with computational modeling. Running the computational model, they found that the accuracy of the orthographic-semantic route increased over time, leading to its improved performance. The indirect route, though, continued to boost the model's performance and improved the accuracy with which the correct semantic representations were selected. In short, both routes were found to play a role in facilitating

the model’s overall performance.

In contrast to the activation-verification and connectionist models, both of which assume that reading always entails a certain degree of prelexical phonological activation, the dual-route cascaded model of reading (Coltheart et al., 2001; Coltheart, 2005, 2006) posits that readers can access meaning either directly (from orthography to meaning, bypassing phonology) or indirectly (from orthography to meaning via phonology). The strength of the direct route, however, must develop over time and is not available to early readers. Children in the “sounding out” stage of reading development would thus rely largely or entirely on the phonological route, decoding text via letter/grapheme mapping rules (Share, 1995). As their familiarity with a word increases following repeated exposure, the contribution of the indirect phonological route decreases, and the direct route is strengthened. Once developed, the direct route, which bypasses phonology and is thus more efficient, becomes predominant in the reading of skilled readers.

While these models were developed based primarily on research on alphabetic languages, the connectionist and dual-route models have been used to describe reading processes in Chinese as well. Despite the differences between these scripts, C. A. Perfetti et al. (1992), as well as C. A. Perfetti et al. (2005), have argued that meaning is accessed in much the same way regardless of script (see Chapter 2 for discussion of phonological activation patterns in Chinese and English reading). However, phonological activation in English can occur at the phoneme level, but in Chinese, phonological activation can only occur at the syllable level as Chinese characters cannot be broken down into phonemes.

Some researchers have used the dual-route and connectionist models to describe deaf reading processes. Elliott et al. (2012), for example, extended the dual-route model to deaf readers, proposing the dual-route cascaded model of reading by deaf adults. They suggested that deaf readers primarily differ from hearing readers, not in terms of the cognitive structure of their reading systems, but in terms of the nature of their phonological units. Phonological representations in deaf readers, they posited, are based on mouth shapes, or *visemes*, acquired through lipreading. As a single viseme can often

map to multiple phonemes (e.g., the phonemes /m/ and /b/ in English would map to a single viseme, as they cannot be distinguished visually by mouth shape), deaf readers' mental lexicons would have more lexical representations that overlap in their phonology. Ormel et al. (2009) proposed a connectionist model that aimed to explain sign activation processes that have been found to occur in deaf reading—the deaf bilingual interactive activation model. According to this model, when deaf readers recognize a printed word, its sign translation equivalent is automatically activated through its orthography. Following this, its sign phonological features (i.e., the specific handshape, movement, location, and hand orientation associated with the sign) are also activated, which then leads to the activation of other sign language lexical representations which share one or more of those sign phonological features.

In sum, the activation-verification (Van Orden, 1987), dual-route (Coltheart et al., 2001; Coltheart, 2005, 2006), and connectionist (Harm & Seidenberg, 2004; Seidenberg & McClelland, 1989) models make different claims about the time course of phonological activation during reading and whether or not its activation is necessary and automatic during the course of word recognition. The dual-route cascaded model of reading by deaf adults (Elliott et al., 2012), as well as the deaf bilingual interactive activation model (Ormel et al., 2009), extend the dual-route and connectionist models to make specific claims about the nature of the phonological units activated by deaf readers during word recognition processes. The models of deaf reading, in particular, have not yet been widely investigated. Furthermore, certain questions remain unaddressed by these models—for example, while there has been evidence of both spoken and sign phonological activation among deaf readers, the relationship between the two types of phonological code remains unclear. More research is needed to understand the time course (e.g., are the two types of code activated simultaneously or during different stages of processing?) and roles of spoken and sign phonological activation in deaf reading processes.

1.1.5 Methodological approach

The focus of this thesis was on understanding the cognitive processes underlying reading in deaf signers from Hong Kong—specifically, to investigate whether they have a phonological route to meaning and whether the phonological code they activate is based on Cantonese, HKSL, or both. If evidence is found of both spoken and sign phonological activation among Hong Kong deaf readers, the question follows as to how the two types of phonological code relate—that is, whether they are activated synchronously and whether they play different roles in facilitating comprehension processes.

Many experiments looking at PCA skills, such as those included in the meta-analyses by Bus and van IJzendoorn (1999) and Mayberry et al. (2011), as well as the reading development studies discussed in this chapter, have used off-line methods involving tasks such as rhyming, spelling or word recall. As these methods are not time-sensitive, they cannot be used to investigate the automatic cognitive processes that underlie reading, but rather serve as a measure of knowledge or skill in the areas they target (e.g., orthography, phonology, or morphology). Even in this respect, it is not always clear that all of these tasks are accurately measuring the skill they are intended to measure. Mayberry et al. (2011) noted that whether certain tasks truly isolate PCA skills at all is not always clear. For example, deaf participants performing poorly on rhyming tasks might be an indication of their lack of familiarity with the concept of rhyme rather than a lack of general PCA skills.

Researchers interested in the timing of automatic cognitive processes that occur during silent reading (e.g., the activation of orthographic, phonological and semantic representations) generally use time-sensitive experimental tasks. Many such studies have measured participants' reaction times as they respond to word-based stimuli. For example, in a lexical decision experiment, participants are presented with a word or pseudo-word and must indicate whether the presented text is a real word by indicating *yes* or *no* with a key-press. When a pseudohomophone is presented, for example *mayd* (a pseudohomophone of *maid* and *made*), participants tend to take longer to reject them than they take

to reject non-word controls that are phonologically dissimilar to any real word (Ziegler et al., 2001). This pattern has been taken as evidence of early phonological involvement in activating word meanings as it suggests that participants are activating the pseudo-homophone’s phonological code, which in turn is activating the lexical representations associated with its real-word homographs and leading to a delay in the participant’s response.

While many reaction time studies using lexical decision and related methodologies have been instrumental in building our understanding of word reading processes, Leinenger (2014) notes that reaction times may not be time-sensitive enough to precisely measure the time course of the orthographic and phonological activation processes leading up to word recognition since actual processing time is confounded by other factors, such as the time it takes to plan and carry out the motor tasks involved in creating a response. Thus, to get a more detailed picture of cognitive processes, some researchers have advocated the use of on-line experiments using specialized technology to measure event-related potentials and eye movements, which can provide a time-sensitive measures of cognitive response (Serenó & Rayner, 2003) without relying solely on participant responses.

Leinenger (2014) also noted a disadvantage of relying on single-word (e.g., lexical decision tasks) studies for investigating orthographic and phonological activation. The goal in normal reading as engaged with on a day-to-day basis, usually at the sentence level or above, is comprehension, but it is not clear that paradigms that use lexical decision and other related judgment tasks (e.g., semantic categorization and relation) are actually engaging these same comprehension processes. Therefore, sentence level tasks may better reflect the kind of reading most people engage in day-to-day.

In reading experiments that use event-related potentials (ERPs), participants read words (often as part of a task, such as lexical decision) or sentences while their electroencephalograms (EEGs) are recorded by a sensor-net placed over the scalp. ERPs are the stimulus-locked brain wave amplitudes (measured in microvolts/ μ V) averaged from the EEG data across multiple trials, and they provide a millisecond-by-millisecond

measurement of brain response to a target stimulus. One of the most well-researched ERP components in language-related studies is the N400, which is a negative-going wave that occurs around 400 ms after the onset of the target stimulus. This component was first reported by Kutas and Hillyard (1980), who found that contextually inappropriate words (compared to contextually appropriate words) at the end of a sentence produced an increased negative brain wave response in readers between 300 and 600 ms after the word’s onset. The N400 has since also been found to reflect phonological activation during reading in both English and Chinese (Liu et al., 2011; Newman et al., 2012; Ren et al., 2009). For example, in a study on skilled readers of English, Newman et al., (2012) found that N400 amplitudes were less negative for homophone errors (e.g., “The hungry bare hunted for food”) than for phonologically dissimilar spelling controls (e.g., “The hungry beer hunted for food”), though only when homophone errors were low-frequency words. However, the earliest phonological effects emerged between 150–200 ms for high-frequency homophone errors. According to the authors, this suggested that phonological representations were activated earlier for high-frequency homophones than low-frequency homophones.

ERPs are useful for investigating cognitive processing as they allow for a high degree of time sensitivity, but a disadvantage of this methodology is that words are usually presented on the screen one at a time using a fixed rate of presentation (e.g., 500 ms per word) to minimize contamination of the EEG with electrical activity generated by eye movements (Duncan et al., 2009).

This degrades the ecological validity of the task as readers no longer have control over the time they can fixate on each word. An alternative method that allows for more natural sentence reading is eye-movement recording, carried out with an eye-tracker. Though less sensitive than ERPs, eye-tracking offers a relatively high degree of sensitivity with the added benefit of allowing participants to read full sentences or passages at their own pace, rather than having to display them one word at a time. Eye-tracking has been used in many reading studies, both on English and Chinese, to investigate the time course of

orthographic and phonological activation (Daneman & Reingold, 2000; Feng et al., 2001; Rayner et al., 1998; Tsai et al., 2004; Wong & Chen, 1999; Zhou et al., 2018).

In a complementary study to Newman et al.’s (2012) ERP study, Jared and O’Donnell (2017) carried out an eye-tracking study with skilled readers that used the same experimental stimuli—though, in this study, sentences were presented on the screen in full rather than one word at a time. They found that first fixation durations (the length of the first fixation on a target in milliseconds) and gaze durations (the first fixation duration plus the length of any refixations before the reader’s eyes move outside the target word region) on high-frequency homophone errors (e.g., “From my office, I can sea the entire city”) were shorter than fixation times on spelling controls (e.g., “From my office, I can sit the entire city”). When homophone errors were low-frequency words, this difference in fixation times emerged later in a measure referred to as *spillover* (the length of the first fixation on the word after the target). Again, these findings indicated that phonological activation occurred earlier for high-frequency homophones than for low-frequency homophones. In the preceding paragraphs, two studies were discussed briefly, Jared and O’Donnell (2017) and Newman et al. (2012). These studies both focused on skilled readers of English and used the same experimental stimuli, but Jared and O’Donnell (2017) recorded eye movements while Newman et al. (2012) recorded ERPs. The ERP evidence showed that participants were activating phonological representations for high-frequency homophones in an earlier time window than low-frequency homophones. The eye-tracking study provided further evidence of this pattern—significant effects of high-frequency homophone errors in earlier fixations and significant effects of low-frequency homophones only in later fixations. Together, the results of these two studies make a strong case that skilled readers activate phonology during reading and that this process can be modulated by word frequency.

The aim of this thesis is to investigate the roles and time-course of orthographic and phonological processing in deaf readers, so a felicitous experimental methodology would be highly time-sensitive and resemble natural reading to the greatest extent possible.

Both eye-movements and ERPs have distinct advantages in this regard for researching reading processing. ERPs offer a high degree of time sensitivity, while eye-tracking sacrifices some time sensitivity for improved experimental ecology. Sereno and Rayner (2003) have suggested that both technologies can be used in complementary ways to take advantage of the benefits offered by each, and a specific example of this approach (Jared & O'Donnell, 2017; Newman et al., 2012) has been discussed. To build a robust picture of reading processes in deaf readers, a similar methodological approach was adopted in conducting the research for this thesis, which has resulted in four studies, three of which used eye-tracking, and one which used ERPs.

1.1.6 Structure of this thesis

The next four chapters (Chapters 2–5) present four experimental studies carried out to answer research questions related to the primary aim of this thesis, which is to examine orthographic, spoken phonological, and sign phonological processing in Hong Kong deaf readers. These studies are presented as stand-alone articles and have been published in academic journals or are currently undergoing peer review. Ethical clearance was attained for all studies from the University of Melbourne, and additional ethical clearance was attained from The Chinese University of Hong Kong for the studies in Chapters 3, 4 and 5 (which were carried out on The Chinese University of Hong Kong's campus). All participants gave written consent and received a small payment for their participation. The following paragraphs give an overview of the remaining chapters of this thesis and the research questions¹ addressed by each.

Chapter 2 presents the first study, which was an eye-tracking study focusing on hearing readers of Chinese from Hong Kong and was conducted at the University of Melbourne. This study was designed to answer two research questions for this thesis. The first research question (RQ1) was, “What is the time course of orthographic and

¹Note that, as each chapter is a stand-alone research paper, the research questions stated within each chapter will deviate from the more general research questions listed here, often addressing more specific theoretical issues that are less closely related to the central aim of the thesis.

phonological activation in Cantonese-speaking readers of Chinese?”

In designing the experiments, it was considered that deaf readers might not activate phonology in sub-optimal conditions but may do so in special conditions that facilitate phonological activation. Eye-tracking studies on English have shown that when targets appear in highly predictable conditions, phonological activation effects are more likely to emerge. Only one eye-tracking study investigated this phenomenon in Chinese, but found no effect (Feng et al., 2001). However, given some methodological issues with this study (discussed in Chapter 2) and counter-evidence from ERP studies, suggesting that Chinese readers do activate phonological representations in high predictability contexts (Liu et al., 2011; Ren et al., 2009), this issue was reinvestigated in the Chapter 2 study. Thus, the second research question (RQ2) for this thesis was, “Can phonological activation in Chinese reading be modulated by contextual predictability?”

Chapter 3 presents the second study, which was an eye-tracking study carried out in Hong Kong that focused on deaf signers. The methodology closely followed that used in the Chapter 2 study. The primary research question for the Chapter 3 study (RQ3) was, “What is the time course of orthographic and phonological activation in Hong Kong deaf readers?” Similar to the study in Chapter 2, this study also looked at whether orthographic and phonological processing could be modulated by contextual predictability. Furthermore, as some research has suggested that using phonological code might be a feature of skilled deaf readers (M. Yan et al., 2015), the influence of reading level was also examined. Thus, the fourth research question (RQ4) for this thesis was, “How are orthographic and phonological processing modulated by contextual predictability and reading level?”

The last goal of this study was to test Elliott et al.’s (2012) dual-route cascaded model of reading by deaf adults to investigate whether Hong Kong deaf readers’ phonological representations were based on visemes/mouth shapes rather than the sound-based phonological representations of hearing readers. Therefore, the fifth research question (RQ5) for this thesis was, “What is the nature of phonological units in deaf readers’ mental

lexicons?” To answer this question, a homovisemic condition was included.

In **Chapter 4**, the focus moves from investigating spoken phonological activation to sign phonological activation. The experiment in this chapter used a parafoveal preview paradigm with eye-tracking. As most deaf signers in Hong Kong are educated orally, it was not certain that they would activate sign representations when reading Chinese. Thus, the first research question for this chapter (RQ6) was, “Do Hong Kong deaf readers activate HKSL representations during reading?”

Going beyond the general question of whether sign phonological activation occurs, another question of interest was how sign phonology influences processing. Some researchers have suggested that different sign phonological parameters—namely handshape, location, and movement—have different roles in reading processing (Chiu & Wu, 2016; Kubus et al., 2015; Morford et al., 2019), but none have investigated this systematically. Thus, this study aimed to address this by answering the next research question (RQ7), which was, “How do the different HKSL phonological parameters of handshape, location, and movement affect reading processing?”

Chapter 5 presents the final study for this thesis, which used two different error disruption paradigms with ERPs—one focused on orthographic and spoken phonological processing and one focused on sign phonological processing. The first aim of this study is to answer the research question (RQ8), “Is there evidence of orthographic, spoken phonological, and sign phonological modulation of ERP components in Hong Kong deaf readers?”

Furthermore, the evidence seems to suggest that deaf readers activate both spoken and sign phonological representations during reading. For instance Elliott et al. (2012) mentions in describing the dual-route cascaded model of reading that the spoken and sign phonological lexicons overlap.

In the discussion on cognitive models of deaf reading, it was noted that, while researchers have widely recognized that both spoken and sign phonology play some role in deaf reading, no research has tried to examine the relationship between these two types

of phonological code. For example, it is unclear whether these codes are activated in parallel or at different stages of processing. This leads to the next research question (RQ9): “What is the relative time course of spoken and sign phonological activation?” The final aim of this study was to see whether ERP evidence can bolster the findings from the earlier eye-tracking studies. Thus, the final research question (RQ10) is, “Does evidence from ERPs converge with the eye-tracking data of the previous studies?”

The final chapter, **Chapter 6**, summarizes Chapters 2–5 and discusses how the findings of each study contributed to the overall aim of building an in-depth picture of orthographic and phonological processing in Hong Kong deaf readers and respond to each of the ten research questions just outlined. Finally, this research project is drawn to a close with a discussion of the theoretical and practical implications of the findings, in addition to methodological issues and directions for future research.

Chapter 2

The effect of word predictability on phonological activation in Cantonese reading: A study of eye fixations and pupillary response (accepted version)

Abstract

This study aimed to investigate the effects of contextual predictability on orthographic and phonological activation during Chinese sentence reading by Cantonese-speaking readers using the error disruption paradigm. Participants' eye fixations and pupil sizes were recorded while they silently read Chinese sentences containing homophonic, orthographic, and unrelated errors. Sentences had varying amounts of contextual information leading up to target words such that some targets were more predictable than others. Results of the fixation time analysis indicated that orthographic effects were significant in first fixation and gaze duration, while phonological effects emerged later in total reading time. However, interactions between predictability and the homophonic condition were found in gaze duration. These

results suggest that, while Cantonese readers activate word meanings primarily through orthography in early processing, early phonological activation can occur when facilitated by semantics in high-constraint sentence contexts. Analysis of pupillary response measurements revealed that participants' pupil sizes became larger when they read words containing orthographic errors, suggesting that orthographic error recovery processes significantly increase cognitive load.

2.1 Introduction

A major goal among researchers investigating the cognitive processes involved in silent reading has been to untangle the roles of orthography and phonology in relation to semantic access. One view is that word identification first involves the activation of a mental representation of the word's phonological form, which in turn allows access to the word's meaning (Frost, 1998; Van Orden, 1987). Another view, referred to as the dual-route model (Coltheart et al., 2001), proposes that while reading the semantic system can be accessed either directly through orthography or via an indirect route by which orthography first activates phonology, which then in-turn activates meaning. According to this model, the more efficient direct route from orthography to meaning is predominant in skilled reading, but both routes can receive varying degrees of simultaneous activation. Whether phonological activation occurs prior to lexical access has been found to depend upon a complex interplay of factors including the skill of the reader, the frequency of the word, and the predictability of the word in context (see Leinenger, 2014, for review of relevant studies). However, as the development of theories of reading has primarily relied on experimental data from studies on readers of English and other alphabetic languages, the issue of how factors such as word frequency and context affect reading in non-alphabetic languages, such as Chinese, remains underexplored.

2.1.1 Chinese and alphabetic writing systems

In alphabetic writing systems, letters map to individual phonemes, which are combined to form words. Even unfamiliar words in alphabetic languages like English can be assembled letter-by-letter via a successive grapheme-phoneme mapping procedure and pronounced aloud. A word like *wug*, for example, can be broken down into /w/, /ʌ/, and /g/. In contrast, no element within a Chinese character corresponds to an individual phoneme. Rather, the character maps to a single syllable. Most Chinese characters are composed of semantic and phonetic radicals, which give information related to the meaning and pronunciation of the character. For example, the character 估 /gu2/ [estimate], consists of the semantic radical 亻 [person] and the phonetic radical 古 /gu2/¹ [ancient]. Importantly, nothing in the characters 估 /gu2/ [estimate] or 古 /gu2/ [ancient] represents the phonemes /g/ and /u/ or the tone.

There are two important points to note regarding the phonetic information contained in Chinese characters. The first is that while many Chinese characters contain phonetic radicals (e.g., 估 /gu2/, discussed above), the information conveyed by these radicals is often unreliable or inconsistent. For example, in the character 猜 /caai1/ [guess], the radical 青 /cing1/ [green] has a different pronunciation than the character as a whole. Only around 26% of Chinese characters have a pronunciation that corresponds to their phonetic radicals, and only between 14% and 46% have meanings that are clearly related to their semantic radical (Gao et al., 1993)—e.g., 蟻 [ant] containing the semantic radical 虫 [insect]. Secondly, many characters have the same pronunciation, even though they might be orthographically unrelated (e.g., 股 /gu2/ [a share] and 古 /gu2/ [ancient]). There is an average of approximately 17 homophonic characters per base syllable in Cantonese (total of 625 base syllables—1761 with tones; LSHK, 1997) and 31 characters per syllable in Mandarin (420 base syllables—1471 with tones; Denisowski, 2005).

To summarize the points above, there are three different facts regarding Chinese that distinguish it from alphabetic systems and that are relevant to the current study: 1) each

¹Chinese pronunciations shown in the Cantonese romanization system, Jyutping.

Chinese character represents a full syllable and cannot be broken down into individual phonemes; 2) orthographic cues indicating a character’s pronunciation are inconsistent, and characters with entirely different orthographic structures might share the same pronunciation; 3) there are a large number of homophonic characters in Chinese, though these homophones might vary in terms of orthographic relatedness. In light of these unique characteristics associated with Chinese script, C. A. Perfetti et al. (1992) proposed the universal phonological principle in order to address the question of how these characteristics might affect phonological processing during Chinese reading. This view purports that, across scripts, phonological activation automatically proceeds from the visual identification of words, and the unique properties of individual writing systems determine how phonological activation unfolds. While not necessarily used for lexical access, the activated phonological representations are important for reading comprehension and retaining words in memory. Reading processes in Chinese only differ from alphabetic languages in that Chinese word activation is necessarily a two-step process: once orthographic identification is complete, the character’s phonology is activated at the syllable level. Alphabetic languages, in contrast, allow for earlier phonological activation, beginning at the phonemic level with grapheme units, before full orthographic recognition at the word-level is achieved.

2.1.2 Homophones and the error disruption paradigm

In Chinese, many characters are homophonic in that they share a pronunciation but may be entirely dissimilar in orthographic structure. For example, the characters 估 [estimate], 古 [ancient], 股 [a share], and 鼓 [drum] all share the Cantonese pronunciation /gu2/ but vary in terms of shared visual similarity. In the case of English, homophones necessarily overlap in orthographic structure. For example, “bare” and “bear” share the same letters in addition to their identical pronunciation. Even homophone pairs that share fewer orthographic similarities, such as “chute” and “shoot,” share some of the same letters. Therefore, while homophones exist in both languages, Chinese homophones differ from

English ones in that many Chinese homophone pairs are orthographically unrelated.

In the error disruption paradigm, participants silently read sentences containing either orthographic errors or homophonic errors while their eye-movements are recorded by an eye-tracker to investigate the time course of phonological and orthographic activation during sentence or passage reading. When analyzing eye-tracking data obtained through such studies, researchers are interested in the time readers spend reading each homophone or orthography error. Three commonly used measures of reading time include first fixation duration (FFD; the duration, in milliseconds, of the first fixation on the target word), gaze duration (GD; the duration of the first fixation in addition to any refixations made before the reader moves on to the next word), and total reading time (TRT; the total duration of all fixations made on the target word, including regressive fixations made after the reader has already fixated on any word outside the target region). FFD and GD are generally considered similar in that they both reflect early stages of processing during which words are retrieved from the mental lexicon (Rayner, 1998, 2009), though some researchers have argued that GD is more closely tied to semantic integration processes (Carpenter & Daneman, 1981; Inhoff, 1984). TRT is considered a measure of late stages of word processing and integration (Conklin et al., 2018) as well as error decoding and recovery (Daneman & Reingold, 1993).

In English, when homophone errors (e.g., “*They decided that they would **meat** at twelve o’clock for lunch*”) are fixated on for shorter periods of time than orthographic controls (e.g., “*They decided that they would **mean** at twelve o’clock for lunch*”), it is taken to indicate that phonology is being involved in activating the meaning of the correct target word (see Daneman & Reingold, 2000, Rayner et al., 1998). Chinese error disruption paradigm experiments have generally included, at minimum, a correct condition (e.g., 自 /zi6/ [self] in 自己 /zi6 gei2/ [self]), an orthographic error condition (e.g., 目 /muk6/ [eye]), a homophonic error condition (e.g., 字 /zi6/ [word]), and an unrelated control error (e.g., 分 /fen1/ [divide]) (see Zhou et al., 2018). Shorter fixations on orthographically unrelated homophonic errors than unrelated errors (e.g., shorter fixations

on 字 /zi6/ [word] than 分 /fen1/ [divide]) would indicate phonological involvement in lexical access. Shorter fixations on orthographic errors, but not on homophonic errors, relative to unrelated controls, would suggest that meaning is being activated primarily through orthography.

Daneman and Reingold (1993) and Daneman et al. (1995) conducted two error disruption experiments in English to look at how homophonic and orthographic errors affected participants' eye-movements while reading a 1100-word passage. They found that both types of error caused similar amounts of disruption to reading speed in GD compared to the correct word. The analysis of later processing measures (e.g., TRT) showed that readers spent significantly less time fixating homophonic errors than orthographic controls. However, this only held true for homophone pairs of the same length (e.g., blue and blew as opposed to wade and weighed). The authors concluded that the role of phonology is more delayed or limited than earlier single-word reaction time studies had suggested (for review of these studies, see Leininger, 2014).

Rayner et al. (1998) carried out a study using a similar paradigm to that of Daneman and Reingold (1993) and Daneman et al. (1995). They hypothesized that high contextual predictability might make it more likely for phonological activation to occur, so they varied the degree of contextual predictability (or “constraint”) to include high-constraint sentences, in which the target was highly predictable (e.g., “*She realized that she was going too fast and needed to slam on the **brake** to slow down*”), and low-constraint sentences, in which the target was less predictable. They also varied the degree of orthographic overlap between homophone errors and orthographic controls (e.g., same initial two letters: *brake/break*; same initial one letter: *bear/bare*; different initial and final letters: *chute/shoot*). When the variables of constraint and orthographic similarity were collapsed, their results reflected those of Daneman and Reingold (1993) and Daneman et al. (1995), who had found only later involvement of phonology. However, they did find evidence of early phonological activation in FFD when both predictability and orthographic similarity were high. They interpreted their data as supporting early and

dominant involvement of phonology in lexical access.

In a later study, Daneman and Reingold (2000) responded to Rayner et al.'s (1998) conclusion that their findings supported pre-lexical phonological activation, pointing out that early phonological activation was only found in high-constraint contexts. Furthermore, they replicated their original study with an additional group of participants and again found evidence of phonological activation only in later measures, suggesting that phonology did not play a role in early lexical access. They concluded that phonological codes play only a limited role in regular reading—mainly in accessing the meanings of low frequency words. In this replication study, to test Rayner et al.'s (1998) finding that early phonological activation could occur when contextual constraint was high, Daneman and Reingold (2000) conducted a norming study to check the predictability of target words in the texts used in their own experiments, inviting a new group of participants to read each target sentence up to but not including the target word and then guess what the next word would be. Based on the results, each sentence was assigned a contextual predictability value (i.e., the proportion of correct guesses). Among the three texts used in their experiment, the text with the highest number of predictable targets had a mean predictability value of .28 ($SD = .33$) with a wide range of scores from 0 (no correct predictions) to 1.0 (all participants guessed correctly). Like Rayner et al. (1998), they also found that higher predictability values correlated with shorter fixation times on homophone errors. However, as high-constraint sentence contexts are relatively uncommon, they argued that this phonological involvement could not be said to generalize to most reading situations. Daneman and Reingold (2000) proposed the following model for reading in these predictable contexts: if a given context is highly constrained, a semantic representation of the predictable target will be activated by context prior to its being fixated. This semantic representation will then, in turn, activate its associated phonological and orthographic representations. If these pre-activated representations match the target, lexical access will be quicker, leading to shorter fixation durations on homophone and orthographic errors. Thus, in high-constraint contexts, phonology is also activated

top-down via semantics rather than only bottom-up through orthography.

The error disruption paradigm was extended to examine orthographic and phonological processing during silent reading in Chinese by Wong and Chen (1999), who conducted an error disruption experiment with Cantonese speaking readers of traditional Chinese characters² from Hong Kong. The experimenters manipulated the first characters of two-character words and embedded them in short passages. Their stimuli contained five conditions: a correct target condition (e.g., 栽培 /zoi1 pui4/ [to grow]), an orthographic condition (e.g., 截培 /zit6 pui4/; similar orthography + dissimilar pronunciation to the correct target), an orthographically similar homophone condition (e.g., 戔培 /zoi1 pui4/; similar orthography + identical pronunciation to the correct target), an orthographically dissimilar homophone condition (e.g., 災培 /zoi1 pui4/; dissimilar orthography + identical pronunciation to the correct target), and an unrelated control condition (e.g., 紗培 /saa1 pui4/; dissimilar orthography + dissimilar pronunciation to the correct target). In FFD, only orthographic errors benefited (i.e., caused less disruption to) fixation times relative to controls. In GD, they found a strong effect of orthography and a weak (i.e., significant across items but not subjects) phonological effect. In TRT, both orthographic and phonological effects were significant. When erroneous characters were both homophonic and orthographically similar, there was an additive effect leading to faster reading times than either homophonic or orthographic similarity alone. The authors concluded that these findings point to a dominant role of orthography in the early stages of processing during Chinese reading and that phonology was activated during the late stage of error recovery. This conclusion was similar to that of Daneman and Reingold (2000)—that meaning is accessed mainly through orthography in normal reading.

To compare the roles of orthography and phonology during silent reading in Chinese and English, Feng et al. (2001) conducted two error disruption experiments, one with native speakers of English and another with native speakers of Mandarin Chinese. In English, phonological benefit was found in FFD, but only when the target was highly

²Traditional characters are those most widely used in Taiwan, Hong Kong, and Macau, in contrast to simplified characters used in Mainland China.

predictable from context and the homophone was orthographically similar to the target (e.g., *creek* and *creak*). Word frequency was also found to play a role in that phonological benefit was found for high-frequency words but not low. The authors concluded that early effects of phonology are found in English but highly constrained by factors such as orthographic similarity, frequency, and contextual predictability. In the Chinese data, they only found phonological effects in the late processing measure of TRT, and this lack of early phonological effects in Chinese held true regardless of orthographic similarity, predictability, and frequency.

While the studies discussed above mainly support direct access to meaning via orthography for skilled readers, studies on developing readers support a more central role for phonological mediation. Among English readers, weaker readers have been found to rely more on phonology for lexical access than more skilled readers (Jared et al., 1999). In their developmental study of Chinese readers, Zhou et al. (2018) conducted an experiment using the error disruption paradigm to compare child ($M = 9.1$ years, $SD = 0.3$) and adult ($M = 22.8$ years, $SD = 2.0$) readers and found that children fixated on homophonic errors for shorter durations than unrelated errors in GD, suggesting that phonological activation was helping them access word meanings. As with other studies, phonological activation only occurred among adult readers in late processing measures.

In sum, these studies suggest that in normal reading conditions, skilled readers of Chinese and English access meaning directly through orthography. However, manipulating certain conditions, such as contextual predictability and word frequency, might facilitate very early phonological activation in English. Less skilled readers of both languages also appear to rely more on phonology in earlier stages of reading development.

2.1.3 Pupillary response

Eye fixation measurements have been widely used in studies on reading, but less attention has been given to pupillary response, which can also be measured by many widely used eye-tracking devices. While most changes in pupil size relate to light or accom-

modation response, tiny pupil diameter increases (less than 0.5 mm) have been shown to reflect increases in cognitive processing demands (Beatty & Lucero-Wagoner, 2000). Pupil size changes measured during experimental tasks have been found to be associated with memory load (Peysakhovich et al., 2015), attentional processing (Ariel & Castel, 2014), uncertainty (Friedman et al., 1973; Steinhauer & Zubin, 1982), lexical ambiguity (Ben-Nun, 1986), and contextually unexpected stimuli (Raisig et al., 2012).

Only a relatively small number of studies have used pupil measurements as a measure of cognitive load during reading tasks, and to our knowledge, none have investigated Chinese reading. Briesemeister et al. (2009) recorded pupil size measurements in addition to EEG and response time during a lexical decision task that included real words, pseudohomophones (e.g., *brane* for *brain*), and orthographic controls (e.g., *brine*). After being presented with each stimulus item, participants had to indicate whether it was a real word or a non-word using designated response keys and then rate how confident they were in their judgment on a 7-point scale. Analysis of pupil size found greater mean peak pupil diameter for pseudohomophones compared to real words and spelling controls. Furthermore, pupil size inversely correlated with confidence ratings, such that pupil diameters were greater when participants were less confident in their word judgments, suggesting that pupil size can reflect conflict monitoring processes. They concluded that the evidence for conflict processing in behavior and pupillometric data is partially the result of phonological activation, as evidenced by the EEG data, which showed a reduced N400³ for pseudohomophones relative to spelling controls.

In one of the few studies on pupillary response during sentence reading, Hyönä and Pollatsek (2000) conducted two Finnish reading experiments in which they analyzed pupil diameter changes during first and second fixations on compound words embedded in sentences. For each compound, they varied the frequency and length of the first and second words (overall length was held constant). Contrary to expectation, they

³The N400 is a negative-going potential which peaks around 400 ms after the onset of the stimulus. Priming studies have shown its amplitude to be affected by various properties of the prime such as orthographic, phonological and semantic relatedness.

did not find that less frequent words evoke increases in pupil diameter. However, they did find consistent significant differences between first and second fixation pupil sizes, suggesting that more processing effort is exerted on the first fixation during the stage of word identification.

In single word reading tasks, pupil dilations in response to stimulus onset tend to occur with a delay of about 300 ms, while single fixations tend to last only around 250 ms (Hoeks & Levelt, 1993). Some researchers might, therefore, question whether analyzing pupillary response on word fixations in sentence reading tasks is appropriate given that the reader might move on to the next word before pupil diameter changes can develop. Hyönä and Pollatsek (2000) argued that because the processing of words begins before the word is directly fixated (i.e., while it is visible in the parafoveal range of vision⁴), changes in pupil diameter will begin to develop earlier in sentence reading tasks than they would in single-word tasks. The early development of pupillary response due to parafoveal processing effects has been supported by a study by Snell et al. (2018) which found that pupil size is affected by the brightness of parafoveally presented stimuli at around 200 ms after onset and that an effect of orthographically related stimuli, also presented in the parafoveal range of vision, developed around 500 ms after onset.

In sum, measuring changes in pupil diameter can tell us about processing load during reading tasks. Furthermore, orthographic and phonological relatedness, as well as contextual predictability, all have been found to influence pupillary response, suggesting it could be a useful addition to more common eye-tracking measures in experiments that employ the error disruption paradigm.

2.2 The present study

In the present study, we use an error disruption paradigm experiment to test Daneman and Reingold (2000) model of reading in predictable contexts, which proposed that when

⁴During reading, the parafoveal range encompasses 1–2 words beyond the word being directly fixated (Vasilev & Angele, 2017).

a target word is highly predictable, its associated orthographic and phonological representations can be activated before the word is fixated. Chinese is different from English in that two orthographically similar characters may have entirely different phonological forms, and two phonologically similar characters may not share any similarities in orthography. Because Chinese is unique in that it allows us to decouple orthography and phonology in this way, it is an optimal script for testing Daneman and Reingold (2000) model, and for investigating whether both phonological and orthographic representations can be activated via semantics.

While Feng et al. (2001) did include contextual predictability as a variable in their study and found no significant effects among the Chinese readers, there are a couple of methodological issues that have led us to reinvestigate this topic. The first is that, in addition to contextual predictability, the authors also manipulated the orthographic similarity and frequency of target words. These two variables were collapsed together when analyzing the effects of predictability, making their findings somewhat difficult to interpret. Secondly, in Feng et al.'s (2001) norming tests, participants were given the passage up to, but not including, the target and asked to make five guesses of what they thought the next word would be. Because predictability values were the probability of correctly guessing the target within five guesses, the high predictability contexts were most likely not as constrained as those used in Daneman and Reingold (2000) and Rayner et al. (1998), whose norming tests only allowed for one guess.

From a theoretical standpoint, if Daneman and Reingold (2000) were correct that contextual predictability allows for the top-down activation of orthographic and phonological representations via semantics—occurring even before the target is fixated—we should expect to see early effects of predictability on orthographic and homophonic errors in both Chinese and English scripts. However, if our results, like Feng et al.'s (2001), show no effect of contextual predictability on the reading of homophonic and orthographic errors in Chinese, it would suggest that the phonological effects found in studies on English reading might be the result of a mechanism other than that described by Daneman and Reingold's

(2000) model. For these reasons, we believe this question is worth re-examining.

Finally, while several eye-tracking studies have used an error disruption paradigm to examine how eye fixations reflect orthographic and phonological activation during Chinese reading, none has incorporated pupil diameter measurements to examine changes in cognitive demand. We hypothesize that fixation times will reflect the findings of earlier studies on Chinese, wherein orthographic errors will provide processing benefit (evidenced by shorter reading times) over unrelated controls in the earlier processing measures of FFD and GD. In contrast, both homophone errors and orthographic errors will provide benefit over controls in TRT. Based on the findings of Briesemeister et al. (2009), we expect that changes in pupil diameter may follow a similar pattern of increased pupil size for character errors relative to correct targets and that unrelated errors might induce greater pupil diameter increases than homophone and orthographic errors.

2.3 Method

2.3.1 Participants

Participants were twenty-eight native Cantonese speakers (age $M = 21.21$, $SD = 2.88$) who had attended primary and secondary school in Hong Kong or Macau and were residing in Australia at the time of the study. On average, participants had been in Australia for around 2.5 years ($SD = 2.2$), and all reported returning to their home cities regularly. All participants had normal or normal-corrected vision and were paid for their participation. Ethical clearance was obtained from the University of Melbourne’s Human Ethics Sub-Committee (HESC) before carrying out the study.

2.3.2 Materials

We selected twenty sets of traditional Chinese characters, each set containing a correct character (e.g., 木 /muk6/ [wood] in 木頭 /muk6 tau4/ [wood]), an orthographically

similar character (e.g., 本 /bun2/ [origin]), a homophonic character (e.g., 目 /muk6/ [eye]) and an unrelated control character (e.g., 充 /cung1/ [to fill]). Orthographic, homophonic, and unrelated character substitutions were not semantically related to their correct mates. To confirm this, we calculated semantic relatedness scores on a 0–1 scale (low–high relatedness) using HowNet (Dong et al., 2006), a Chinese semantic database for natural language processing which can produce similarity ratings that approximate those given by human judges (Dai et al., 2008). Semantic relatedness was low overall ($M = .3$, $SD = .29$), and an analysis of variance showed no interaction between semantic relatedness and condition [$F(2, 57) = 2.1$, $p > .1$].

None of the characters were phonograms (i.e., characters that contain a phonetic radical on the right side, such as 估 /gu2/ which contains the phonetic radical 古 /gu2/). Wherever possible, we matched orthographic, homophonic, and unrelated characters with the correct character for strokes ($M = 6.69$, $SD = 2.42$) and frequency ($M = 166$, $SD = 118$ per corpus unit in H. H. Ho & Kwan, 2001). There were no significant differences across conditions for either [strokes: $F(3, 76) = 1.16$, $p > .1$; frequency: $F(3, 76) = 1.80$, $p > .1$]. Due to the limited number of traditional Chinese character pairs with high orthographic similarity, we included four less-common characters in the orthographic condition, each with a frequency of seven or fewer per 660,000 characters, such as 戍 /syu3/ as the orthographic mate to 戕 /sing4/. To confirm that none of our findings could be attributed to the presence of these less-common characters, we ran a second statistical analysis on a subset of data that excluded trials associated with these characters and found they did not affect patterns of significance.

We selected characters for the orthographic condition based on visual similarity to correct targets, which differed in orthographic structure by no more than two strokes. To confirm that readers would perceive these characters as orthographically similar to their correct mates, we conducted a norming study with twenty native Cantonese speaking participants who did not take part in the experiment. These participants were asked to judge how similar the orthographic, homophonic, and unrelated characters were to the

corresponding correct targets in terms of appearance on a scale of one (highly dissimilar) to five (highly similar). As expected, there was a significant effect of condition on orthographic similarity [$F(1, 19) = 110.77, p < .001$]. The orthographically similar characters ($M = 3.6, SD = 1.3$) were rated as significantly more similar to targets than homophonic ($M = 1.3, SD = 0.8; p < .001$) and unrelated characters ($M = 1.3, SD = 0.08; p < .001$) while homophonic and unrelated characters did not differ significantly in their overall similarity rating ($p > .1$). A summary of character properties is presented in Table 2.1.

	Correct	Orthographic	Homophonic	Unrelated
	上	止	尚	以
Example	/soeng6/ [above]	/zi2/ [stop]	/soeng6/ [esteem]	/ji5/ [with]
Frequency	214 (120)	137 (121)	129 (100)	183 (118)
Orthographic Rating	—	3.6 (1.3)	1.3 (0.8)	1.3 (0.8)
Semantic Relatedness	—	.34 (.38)	.19 (.17)	.36 (.35)
Stroke Count	6.3 (2.5)	6.5 (2.0)	7.6 (2.5)	6.5 (2.7)

Table 2.1: *Character properties*. *SDs* in parentheses. Mean frequencies from H. H. Ho and Kwan’s (2001) Hong Kong corpus. Semantic similarity calculated using the HowNet (Dong et al., 2006) database.

As eye fixation measures were based on the two-character word level (following Feng et al., 2001, Wong & Chen, 1999, Zhou et al., 2018), each correct target character was embedded as the first character in three to four different two-character word-frames (e.g., 自 [self] was embedded into 自己 [oneself], 自由 [freedom], 自然 [natural], and 自殺 [suicide]). Due to the limited number of words available for some characters, six word-frames were used twice, though never in the same sentence frame or condition within a single stimulus list. All words were common, with most taken from the Hong Kong Primary School Vocabulary Learning List (Chan, 2007) to ensure that all participants would easily recognize them.

Eighty sentence frames, each containing varying amounts of contextual information before the target, were collected from online sources. Each sentence was 20–25 characters in length with target words appearing at least two words in distance from the beginning

of the sentence or any punctuation marks. Alternative versions of each sentence were created for the three error conditions by replacing the first character of the target word with an orthographic, homophonic, or unrelated substitution. The resulting character pairs never formed a legal word. From these sentences, we created four stimulus lists, each containing the same 80 sentence frames. Within each list, there were 20 correct sentences, 20 with a homophonic error, 20 with an orthographic error, and 20 with an unrelated character error. We used a within-items design such that the second character of the target word, as well as sentence frames, were identical across conditions (see Table 2.2 for examples), and the pairing of sentence frames and targets was counterbalanced across lists so that no participant was exposed to the same sentence frame or target character more than once. A native Cantonese-speaking research assistant from Hong Kong assisted in stimuli design and editing.

Condition	Sentence
Correct character 成績 /sing4 zik1/ [grade]	四年前, 阿明以優異的學習 <u>成績</u> 畢業於哈佛大學. “Four years ago, A-ming graduated from university with exceptional grades.”
Orthographic error 戍績 /syu3/+/zik1/ [garrison]+[merit]	四年前, 阿明以優異的學習 <u>戍績</u> 畢業於哈佛大學.
Homophonic error 承績 /sing4/+/zik1/ [undertake]+[merit]	四年前, 阿明以優異的學習 <u>承績</u> 畢業於哈佛大學.
Unrelated error 去績 /hoei3/+/zik1/ [go]+[merit]	四年前, 阿明以優異的學習 <u>去績</u> 畢業於哈佛大學.

Table 2.2: *Set of example sentences.* A set of example sentences used across the four item lists in the experiment. Target words are underlined for clarity.

Because this study is looking at the effects of contextual predictability, another norming study was conducted with 20 participants not involved in the experiment wherein they were presented with each sentence frame up to but not including the target word and given one open-ended guess as to what word was most likely to come next. Scores ranged from 0 (no correct guesses) to .95 (the target character was correctly guessed around 95 percent of the time—or by 19 out of 20 participants). Twenty-eight sentences were neutral with 0 correct guesses (targets included 4 adjectives; 7 adverbs; 11 nouns; 6 verbs); twenty-six had predictability values between .05 and .25 (7 adjectives; 2 adverbs; 4 nouns; 2 prepositions; 11 verbs), and twenty-six had predictability values between .3 and .95 (3 adjectives; 14 nouns; 9 verbs). The overall mean predictability of targets for all sentences was .22 ($SD = .27$). Predictability values did not correlate with sentence length, target frequency, or target stroke count ($ps > .1$). Table 2.3 shows four example sentences, along with their corresponding predictability values.

Predictability Value	Sentence
.9	列車的冷氣系統故障令多名 <u>乘客</u> 感到非常不舒服。 “The failure of the train’s air-conditioning system caused many passengers to be very uncomfortable.”
.7	傳統上，伴郎負責保管結婚 <u>戒指</u> 以及幫忙打扮新郎。 “Traditionally, the best man is responsible for keeping the wedding ring and helping the groom.”
.4	家人不在時，他根本不會照顧 <u>自己</u> 或者獨立生活。 “When his family is absent, he cannot take care of <u>himself</u> or live independently.”
0	組織者和出席者都對這次 <u>集會</u> 活動感到很滿意。 “Both organizers and attendees were very pleased with the <u>rally</u> this time.”

Table 2.3: *Set of example sentences of different predictability values.* A set of example sentences with a range of predictability values. Target words are underlined. The sentence with a .9 predictability value has the most predictable target word while the sentence with a 0 predictability value has the least predictable target word.

2.3.3 Apparatus

Eye movements were recorded using an SMI RED-n Scientific eye-tracking device with a sampling rate of 60 Hz. The manufacturer reports the device’s spatial resolution as 0.05° and gaze position accuracy as 0.4° . This model was designed to be used without head restriction to allow for greater ecological validity and uses dynamic algorithms to compensate for head movements when calculating fixation times and pupil sizes. Lower-frequency eye-tracking systems, such as the 60 Hz RED-n Scientific used in the current study, tend to have a higher error rate than high-frequency eye-trackers more commonly used in reading research. For instance, a 60 Hz eye-tracker would have an average error rate of around 8 ms, compared to only around 0.5 ms for a 1000 Hz eye-tracker (Raney et al., 2014). While this makes 60 Hz eye-trackers inadequate for research on saccadic eye-movements, they are sufficient for research on fixations (Dalmaijer, 2014; Karn, 2000; Leube et al., 2017; Raney et al., 2014), which are the primary measure used in the current study. Furthermore, lower frequency remote eye-trackers perform comparably to higher frequency ones in their pupil size measurement capabilities (Titz et al., 2018) and have even been used successfully even in pupillometric studies that allow some degree of head movement (Coyne & Sibley, 2016; Klingner et al., 2008). In contrast to Eyelink eye-tracking systems, which output pupil size data in either arbitrary units or pixels, the Red-n Scientific system can output pupil size data in millimeter units, which facilitates pupillometric data analysis. The experiment was run on an HP EliteBook 850 laptop PC (processor, Intel Core i7 running at 2.6 GHz; operating system, Windows 7) with a 15.6-inch LED monitor (frame rate, 60 Hz; resolution, 1366 by 768 pixels). Participants were positioned 65 cm away from the monitor. Stimuli were single line sentences in traditional Chinese displayed in black on white using the font KaiTi, size 36 with each character equaling 1.1° of visual angle.

2.3.4 Procedure

Each participant performed a 9-point calibration of the eye tracker, followed by a validation of calibration accuracy before beginning the experiment. While the remote eye-tracking system used in our study was designed to compensate to some extent for head movement, participants were asked to avoid overt head or body movements as much as possible when reading the stimulus sentences in order to improve tracking accuracy. Before each sentence, a fixation point appeared on the center-left of the screen, marking the approximate location of the beginning of the sentence. Participants were instructed to fixate on the point and press a keyboard key to present the sentence. They were asked to silently read each sentence at a natural pace and try to understand its meaning regardless of any errors they encountered. Sentence order was randomized, and participants were allowed to rest after 40 sentences. The calibration and validation processes were repeated after the rest period. Participants were asked to rate their comprehension of the previously read sentence on a scale of one to five (1 = unclear in meaning, 5 = clear in meaning) at eight random points during the experiment. These prompts were intended to encourage participants to read for comprehension, and responses were not recorded for analysis. A short practice block of five sentences and a comprehension rating item was included at the beginning to ensure that all participants understood the procedures of the experiment. The entire experiment lasted approximately 30 minutes.

2.3.5 Data analysis

One participant was discarded from analysis due to technical problems with eye-tracker calibration. For fixation time and pupil size data, we discarded trials with missing observations due to blinks, movements, or equipment failure (12% of trials). For all fixation time measures, trials with FFDs over 1000 ms (8% of data) were discarded. For early processing measures of FFD and GD, we discarded trials with GDs over 2000 ms (2% of data), and for the late processing measure of TRT, we discarded trials with TRTs over

3000 ms (2% of data).

Inferential statistics for fixation times were based on planned comparisons between each related condition and the unrelated condition, which served as the reference condition. Fixation time analyses looked at three dependent variables: FFD, GD, and TRT. As pupil size has not previously been examined in an error disruption study, we could not assume that the unrelated condition would elicit the largest change in pupil diameter. Therefore, the correct condition was used as the baseline rather than the unrelated condition.

All data were analyzed in R (Team, 2014) with the lme4 package (Bates et al., 2012). Absolute t -values at or above 1.96 indicate statistical significance at the .05 alpha level. Because fixation time data were positively skewed, generalized linear mixed-effects models (GLMMs) with a Gamma distribution and identity link between the predictors and dependent variables were used, which allowed us to avoid log-transforming the fixation times (Lo & Andrews, 2015). For pupil diameter analysis, standard linear mixed models (LMMs) were used.

The best fits for LMM and GLMM structures were determined by model comparisons using the Akaike information criterion (AIC; Akaike, 1998). Due to overparameterization, models with maximal random structures that included random slopes would not converge. Therefore, random structure was reduced to by-participant and by-item random intercepts (Baayen et al., 2008) with condition and predictability value as fixed effects. As dichotomizing quantitative variables can introduce a number of problems to analysis, such as spurious statistical significance and loss of effect size (MacCallum et al., 2002), predictability values were standardized to facilitate model convergence and incorporated into models as a continuous predictor. The formula used for the FFD, GD, and TRT GLMMs was: (Fixation Time Measure) $\sim$ Condition $\times$ Predictability Value + (1 | Participant) + (1 | Item).

While pupillary diameter changes begin prior to the initial fixation on a target when it is visible in the parafoveal range (Snell et al., 2018), the slow emergence and decay

of pupil size changes makes it likely that these effects continue to develop for several fixations. Thus, we examined the development of pupil size over the first fixation on the target as well as four consecutive fixations after. While this includes fixations that occur after leaving the target region, significant differences in pupil size between conditions can be attributed to the manipulated target words as sentence frames were otherwise identical (see Table 2.2). Fixation number (i.e., first fixation–fifth fixation) was included in models to account for the changes in pupil size over time. As predictability was not found to interact with pupil size and did not improve model fit, this variable was excluded from the final model, which was specified as follows: (Pupil Diameter) $\sim$ Condition $\times$ Fixation Number + (1 | Participant) + (1 | Item).

In the error disruption paradigm, upon noticing patterns in the kinds of errors present in the stimuli, participants might change their reading strategies and become more adept at resolving erroneous characters as the experiment progresses. To check whether participants in our study displayed any such adaptive reading patterns, we built additional models that included trial number as a fixed effect. Predictability was excluded from these models to facilitate model convergence. For conciseness, only significant values are reported for these additional models.

2.4 Results

A full summary of normed means from the raw data is presented for fixations and pupil diameters in Table 2.4. Fixations were measured in milliseconds (ms), while pupil diameters were measured in millimeters (mm). All GLMMs and LMMs can be found in Appendix 1 (Tables 6.1, 6.2, 6.3, and 6.4).

FFDs were significantly shorter on correct targets than on unrelated errors ($b = -100.36$, $SE = 8.63$, $t = -11.64$). Orthographic errors also had significantly shorter first fixations than unrelated errors ($b = -41.31$, $SE = 10.23$, $t = -4.04$). First fixations on homophonic errors were not significantly different from those on unrelated errors (b

	Correct	Orthographic	Homophonic	Unrelated
FFD (ms)	319 (9)	386 (12)	427 (11)	427 (12)
GD (ms)	343 (11)	478 (18)	574 (18)	594 (22)
TRT (ms)	411 (18)	758 (30)	803 (25)	1024 (35)
PD-1 (mm)	3.01 (0.01)	3.04 (0.01)	3.02 (0.01)	3.01 (0.01)
PD-2 (mm)	3.01 (0.01)	3.04 (0.01)	3.02 (0.01)	3.01 (0.01)
PD-3 (mm)	3.02 (0.01)	3.05 (0.01)	3.04 (0.01)	3.04 (0.01)
PD-4 (mm)	3.04 (0.01)	3.07 (0.01)	3.06 (0.01)	3.06 (0.01)
PD-5 (mm)	3.01 (0.01)	3.04 (0.01)	3.01 (0.01)	3.01 (0.01)

Table 2.4: *Eye-tracking measures.* Means for all eye-tracking measures with standard errors in parentheses. Values computed across participants' means. FFD = First fixation duration. GD = Gaze duration. TRT = Total reading time. PD-(#) = Pupil diameter-(fixation number).

= 3.28, $SE = 8.25$, $t = 0.40$). Interactions between predictability and the homophonic condition approached significance ($b = -18.88$, $SE = 9.77$, $t = -1.93$), suggesting that fixations on homophonic errors became shorter as predictability values increased. Other interactions were far from reaching significance [all $\text{abs}(t\text{-values}) \leq 1.34$].

As in FFD, GDs were shorter on correct targets than on unrelated errors ($b = -206.44$, $SE = 11.82$, $t = -17.46$). Orthographic errors had significantly shorter GDs than unrelated targets ($b = -103.05$, $SE = 11.72$, $t = -8.79$) but were not significantly different for unrelated errors and homophonic errors ($b = 2.57$, $SE = 12.39$, $t = 0.21$). There was a significant effect of predictability on GDs in the homophonic condition ($b = -33.55$, $SE = 11.22$, $t = -2.99$), indicating that fixation times on homophonic errors relative to controls tended to be shorter when predictability values were higher. There was no effect of predictability in the correct ($b = -4.74$, $SE = 12.07$, $t = -0.39$) and orthographic conditions ($b = 5.71$, $SE = 10.67$, $t = 0.53$). Predictability effects in GD are visualized in Figure 2.1a.

TRTs were shorter on correct targets than on unrelated errors ($b = -494.82$, $SE = 10.69$, $t = -46.27$). TRTs were also significantly shorter on both orthographic errors and homophone errors than on unrelated errors (for orthographic errors, $b = -246.91$, $SE =$

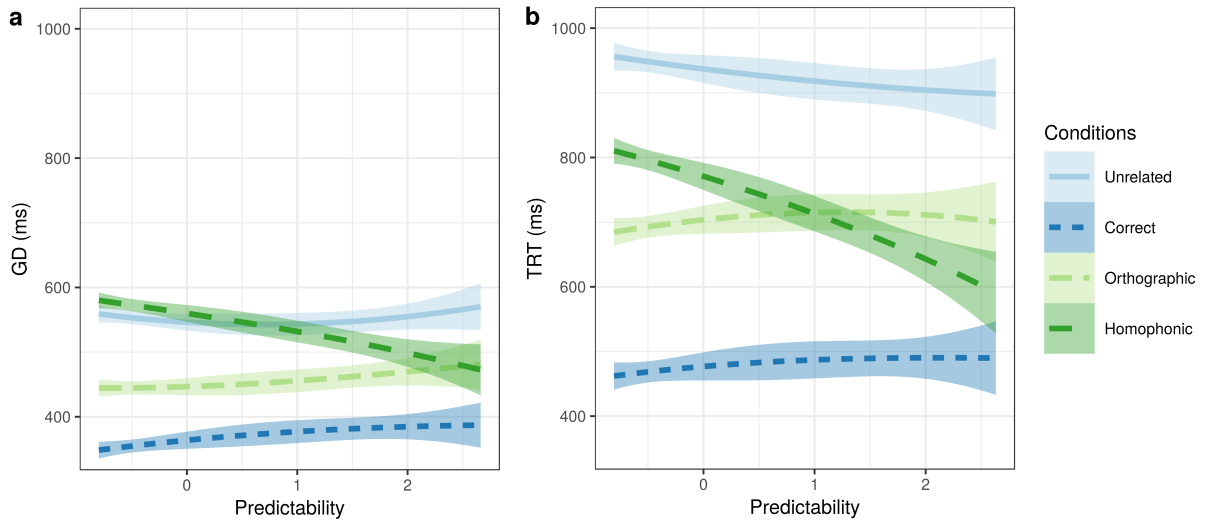


Figure 2.1: *Predictability effects in gaze duration and total reading time.* Readers' gaze durations/GDs (a) and total reading times/TRTs (b) as a function of predictability for unrelated (solid), correct (short-dashed), orthographic (long-dashed), and homophonic (long-dashed, spaced) conditions. The y -axes show fixation times in milliseconds, and the x -axes show predictability values, which have been centered and scaled, from -1 (low-predictable) to 2 (high-predictable). Error bands show 95% confidence intervals.

10.23, $t = -24.14$; for homophone errors, $b = -185.58$, $SE = 10.70$, $t = -17.34$). There was a significant effect of predictability in the homophone condition ($b = -35.60$, $SE = 13.35$, $t = -2.67$), indicating shorter TRTs on homophonic errors when predictability was higher, but not in the correct ($b = 14.22$, $SE = 10.02$, $t = 1.42$) or orthographic conditions ($b = 10.50$, $SE = 12.46$, $t = 0.84$). Predictability effects in TRT are visualized in Figure 2.1b.

Average pupil diameters were significantly larger by approximately 0.03 mm during fixations on orthographic errors than they were during fixations on correct targets ($b = 0.03$, $SE = 0.01$, $t = 2.57$). The interaction between the experimental condition and fixation number was also significant ($b = 0.005$, $SE = 0.003$, $t = 1.99$). Pupil diameters in the homophonic and unrelated conditions were not significantly different than those in the correct condition (homophonic: $b = 0.01$, $SE = 0.01$, $t = 0.86$; unrelated: $b = 0.01$, $SE = 0.01$, $t = 0.62$). Overall, the data suggests that pupil size dilates and then contracts more strongly in the orthographic condition than in the other experimental conditions (see data visualization in Figure 2.2).

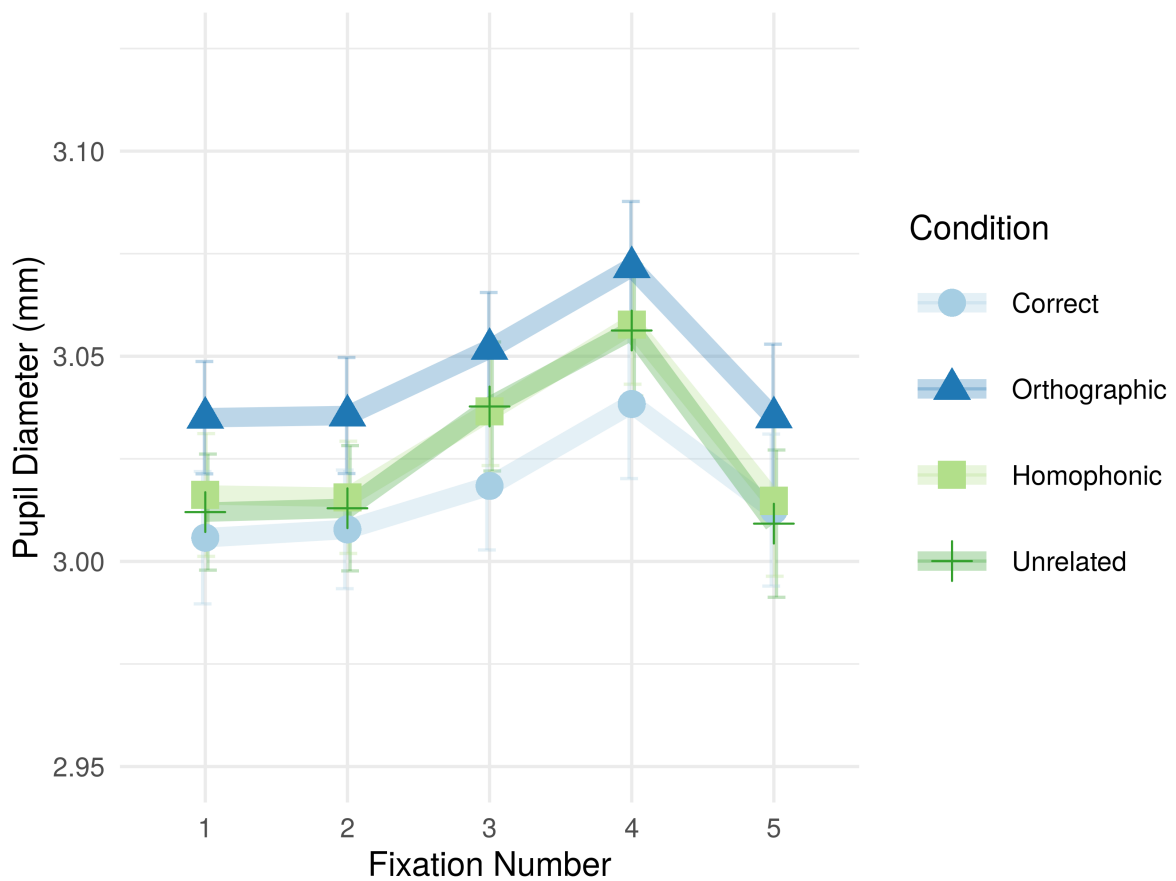


Figure 2.2: *Pupil diameters*. Average pupil diameters during the first target fixation and four consecutive fixations after. Error bars show 95% confidence intervals.

In our follow-up analysis looking at the effects of trial, trial number was found to interact significantly with the reference condition, showing that baseline fixation times became progressively shorter as trials progressed (FFD: $b = -2.16$, $SE = 0.48$, $t = -4.51$; GD: $b = -2.75$, $SE = 0.72$, $t = -3.80$). Importantly, significant interactions were found between trial number and the orthographic condition in FFD ($b = 3.53$, $SE = 0.67$, $t = 5.27$) and GD ($b = 4.31$, $SE = 0.98$, $t = 4.38$), indicating that fixation times on orthographic errors became longer by about 4 ms per trial relative to the unrelated baseline condition. For pupil diameter, interactions between trial number and the orthographic condition were significant ($b = 0.001$, $SE = 0.0004$, $t = 3.08$), indicating that pupil size increases associated with the orthographic condition were greater in later trials.

2.5 Discussion

The primary goal of our study was to test Daneman and Reingold’s (2000) model of meaning activation in predictable texts for Chinese. This model posits that in high-constraint contexts, the phonological and orthographic representations of a predictable word can be activated in early processing via semantics. To test this model, we ran an eye-tracking experiment using an error disruption paradigm. In the experiment, participants silently read sentences that had varying levels of contextual constraint and contained a target word belonging to one of four conditions—correct, orthographic, homophonic, or unrelated. Shorter fixations on orthographic errors (relative to unrelated controls) were taken to indicate lexical access via orthography, and shorter fixations on homophonic errors were taken to indicate lexical access via phonology.

In the early processing measures of FFD and GD, we found significant effects in the orthographic condition, but none in the homophonic condition, suggesting that early lexical access was primarily facilitated by orthography. In the late processing measure of TRT, fixation times were shorter in both orthographic and homophonic conditions, suggesting that both orthographic and phonological information were facilitating error

recovery and integration in late processing. These findings are in line with those of Feng et al. (2001), Wong and Chen (1999), and Zhou et al. (2018) who found that early stages of lexical access were primarily facilitated by the orthographic route in Chinese while the role of phonology was limited to late processing.

Importantly, we found significant interactions between the homophonic condition and predictability values, an effect that emerged in GD and continued into TRT. This finding indicates that readers could more quickly resolve homophonic errors relative to unrelated controls in contexts with high predictability targets. Given that there was no evidence in our data of a robust overall phonological effect in GD when controlling for varying levels of constraint across sentence frames, these results suggest that phonological effects only begin to emerge at higher levels of constraint. This pattern is apparent in Figure 2.1a, where we can see that fixation times on homophonic errors only begin to diverge from those on unrelated errors at the higher end of the predictability range. The linear relationship between higher predictability values and shorter fixation times most likely reflects the fact that higher constraint contexts increase the probability that readers will quickly activate the target phonological form, which then, in turn, facilitates faster lexical access and semantic integration. The pattern of results in our data is in line with the findings of Daneman and Reingold's (2000) study on English reading and thus lends support to their proposal that phonology can be activated early in processing via semantics rather than via bottom-up decoding processes.

While some studies on English reading have found phonological effects emerging in high-constraint sentences in the early processing measure of FFD (e.g., Feng et al., 2001, Rayner et al., 1998), in our study, interactions between predictability and the homophonic condition reached significance slightly later in GD. This might indicate that contextually facilitated early phonological activation in Chinese mainly benefits lexical integration processes rather than initial lexical retrieval. It is also possible that such phonological effects can emerge slightly earlier in English because alphabetic scripts allow phonological activation to begin as soon as individual phonemes are identified. In contrast, Chinese

script necessitates that the full character is identified before its associated phonological form can be activated at the syllable level (C. A. Perfetti et al., 2005).

Diverging from the predictions of Daneman and Reingold’s (2000) model, it is not clear from our findings that orthographic representations are pre-activated by semantics to the same degree as phonological representations as we did not find a significant correlation between predictability values and fixation times on orthographic errors. The finding that phonological activation is closely tied to semantic context and appears to play a role in facilitating lexical access also supports one of the claims of C. A. Perfetti et al.’s (1992) universal phonological principle—that phonology plays an important role across scripts and is involved in facilitating comprehension and lexical integration processes during reading. Based on our results, we suggest that the following process is unfolding when readers resolve homophonic character errors in high-constraint contexts: 1) the target phonological representation is activated via semantics; 2) the reader encounters the homophonic character error, and its component orthographic and phonological representations are immediately activated; 3) the reader matches the phonological form activated bottom-up via the text with the target representation activated top-down by context, thus quickly resolving the error.

It is worth addressing that, in contrast to what some might expect, we did not find an effect of predictability on correct targets. Two studies on readers of English, Rayner & Well, 1996 and Sereno et al., 2017, found that fixations times on low-predictable targets were longer than on medium- or high-predictable targets, but they also found that medium- and high-predictable targets were not significantly different from each other. A study on Chinese readers (G. Yan et al., 2006) found the same pattern of results: significant differences between low-predictable targets when compared to medium- and high-predictable targets but no significant differences between medium- and high-predictable targets. This suggests that while correct targets are read faster in more predictable contexts, this facilitatory effect seems to reach a maximum when predictability values are somewhere between .11 and .67 ($M = .36$), the range for medium-predictability Chinese

sentence items in G. Yan et al. (2006), and fixation times do not appear to decrease further as predictability increases beyond this point. Because 43 out of 80 sentences in our study had predictability values ranging between .1 and .95 ($M = .22$), this maximum facilitatory effect may have already been reached for most items, which might explain why we did not see continually decreasing fixation times on correct targets coinciding with higher predictability values. To test this, we dichotomized the predictability variable, putting sentences with predictability values of 0 into the low-predictable category and those with values above 0 into the high-predictable category. With this change, while we still saw an interaction between predictability and the homophonic condition in GD ($b = 42.60$, $SE = 10.28$, $t = 4.14$), a different pattern of results emerged for the correct and orthographic conditions, showing significant differences between high- and low-predictable conditions for both (correct: $b = 37.58$, $SE = 9.29$, $t = 4.05$; orthographic: $b = 30.26$, $SE = 11.04$, $t = 2.74$). This supports our hypothesis that reading speeds on correct words reach a maximum when predictability values are around .1 and increase little beyond that point. As the practice of dichotomizing variables has been shown in many cases to yield misleading results (MacCallum et al., 2002), and as outcomes in the current study were shown to differ based on whether we treated predictability values as a continuous or dichotomous predictor, researchers looking at predictability effects should put forth careful consideration when deciding which approach to follow.

In addition to the standard fixation time measurements, we examined pupil diameter changes as a measure of cognitive effort and found that orthographic errors elicited more substantial pupillary response effects than the other experimental conditions. On the first fixation, there was a significant effect of the orthographic condition on pupil diameter, indicating that readers' pupil sizes increased when they fixated on orthographic errors. Pupil diameters continued to increase from the second fixation to the fourth and then sharply decreased on the fifth. To check whether pupil diameter increases were a by-product of longer fixation times, we tested for a correlation between pupil diameters and fixation times in the orthographic condition and found no statistically significant

correlation [$r(1620) = .02, p > .1$], suggesting that the significant pupillary response effects we found were not merely due to longer fixations on orthographic errors. The dominant pattern observed across pupil diameter measurements suggested that readers were recruiting increased cognitive resources when resolving errors in which the characters were contextually incorrect but retained strong orthographic likeness to correct targets. This could be evidence that subtle orthographic errors in Chinese induce uncertainty in readers, leading to pupillary response effects similar to those that have been associated with exposure to lexical ambiguities (Ben-Nun, 1986) or pseudohomophones (Briesemeister et al., 2009) in experimental tasks. Future research on alphabetic languages could investigate whether we see pupil size increases associated with orthographic or homophonic errors in sentence contexts. It is possible, however, that the need for increased cognitive resources when reading words with orthographic errors is unique to Chinese, for which reading recruits complex visual processes specially tuned to configural information, similar to those involved in facial recognition (C. Perfetti et al., 2013).

One limitation of the error disruption paradigm used in this study is that, as participants encounter different error types multiple times, they are likely to adapt and adjust their reading style. As part of our analysis, we looked at interactions between our dependent variables and trial number. Importantly, we found that early fixation times (in FFD and GD) and pupil diameters on orthographic errors increased progressively with trial number, suggesting that readers spent more time and exerted more cognitive effort in deciphering orthographic errors in later trials. Conversely, readers spent progressively less time fixating on unrelated errors in later trials. These results suggest that, as participants became more adept in identifying which manipulated characters contained useful cues for error recovery, they began to allocate more time and cognitive effort toward deciphering these errors while also more readily dismissing those identified as indecipherable (i.e., not containing useful orthographic cues) more quickly.

In conclusion, our results point to a primary role of orthography in early processing. However, phonological effects were also found to play a role in early processing

when predictable sentence contexts facilitated top-down activation of phonology. These findings look much like those of Daneman and Reingold (2000), whose studies were on English readers. This suggests that reading processes in both English and Chinese are highly similar under normal reading conditions, and that early activation of phonology via semantics is a phenomenon present in the reading of both scripts. Our study has also shown that increases in pupil size reflect the high degree of cognitive demand recruited by orthographic recovery processes during Chinese reading. Finally, we also found that readers adapt their reading strategies during the error disruption paradigm, allocating more time and cognitive effort toward deciphering orthographic information as the experiment progresses. Follow-up studies investigating the relationship between pupillary response and orthographic processing using different methodologies, such as single-word reading experiments, as well as studies looking more deeply into adaptive reading strategies, would be interesting directions for future research.

2.6 Acknowledgements

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2.7 Supplementary material

Data and R scripts associated with this article can be found at <https://doi.org/10.5281/zenodo.3740873>.

Chapter 3

Orthographic and phonological activation in Hong Kong deaf readers: An eye-tracking study (accepted version)

Abstract

We used an error disruption paradigm to investigate how deaf readers from Hong Kong, who had varying levels of reading fluency, use orthographic, phonological and mouth-shape-based (i.e., “visemic”) codes during Chinese sentence reading, while also examining the role of contextual information in facilitating lexical retrieval and integration. Participants had their eye movements recorded as they silently read Chinese sentences containing orthographic, homophonic, homovisemic, or unrelated errors. Sentences varied in terms of how much contextual information was available leading up to the target word. Fixation time analyses revealed that in early fixation measures, deaf readers activated word meanings primarily through orthographic representations. However, in contexts where targets were highly predictable, fixation times on homophonic errors decreased relative to those on unrelated errors, suggesting that higher levels of contextual predictability facilitated

early phonological activation. In the measure of total reading time, results indicated that deaf readers activated word meanings primarily through orthographic representations, but they also appeared to activate word meanings through visemic representations in late error recovery processes. Examining the influence of reading fluency level on error recovery processes, we found that, in comparison to deaf readers with lower reading fluency levels, those with higher reading fluency levels could more quickly resolve homophonic and orthographic errors in the measures of gaze duration and total reading time, respectively. We conclude with a discussion of the theoretical implications of these findings as they relate to the lexical quality hypothesis and the dual-route cascaded model of reading by deaf adults.

3.1 Introduction

Literacy levels among deaf readers of English often fall behind those of their hearing peers (Mayberry et al., 2011). While the phonemic nature of English and other alphabetic scripts could be an obstacle for deaf learners, educational achievement levels have pointed to similar difficulties in literacy acquisition among deaf readers of Chinese (Thierfelder & Stapleton, 2016). As Chinese is a non-phonemic script that is less closely tied to spoken language than English, it is unclear whether, or to what extent, deaf readers' limited access to spoken phonology affects their acquisition of written Chinese. Even with regard to deaf readers of English, the relationship between phonological coding skills and reading ability remains a topic of debate. Some researchers have argued that weak spoken phonological coding skills among deaf readers could be a significant factor contributing to difficulties in literacy development (Paul et al., 2009; C. A. Perfetti & Sandak, 2000; Y. Wang et al., 2008). Other researchers have argued that variables, such as overall language ability, are of more central importance in facilitating literacy acquisition than phonological coding skills (Allen et al., 2009; Mayberry et al., 2011).

While much discussion has centered around the issue of literacy deficit, research has found that deaf readers exhibit several unique characteristics that set them apart from

hearing readers. For example, deaf readers can take in more information in the parafoveal visual range (i.e., the parafovea, which encompasses one to two words beyond the fixated word for most readers—see Vasilev & Angele, 2017) and process it more efficiently than hearing readers (Bélanger et al., 2018; Bélanger et al., 2013; Bélanger, Slattery, et al., 2012; M. Yan et al., 2015). Despite having limited access to spoken phonology, there is evidence that deaf readers activate phonological code during silent reading (Gutierrez-Sigut et al., 2017; Hanson & Lichtenstein, 1990; Y. Li et al., 2014; M. Yan et al., 2015). Elliott et al. (2012) suggested that those phonological units, rather than being based on acoustic information, are based on mouth shape-based units acquired through lip-reading. Some studies have shown, upon exposure to a word’s written form, deaf readers automatically activate a mental representation of the word’s sign translation (Chiu & Wu, 2016; Meade et al., 2017; Morford et al., 2011; Pan et al., 2015; Thierfelder, Wigglesworth, et al., 2020b), a process which appears to involve action simulation of the sign in the brain’s sensorimotor system (Quandt & Kubicek, 2018).

Still, the topic of cognitive processing in deaf readers remains understudied. Most research has focused on deaf readers in English-speaking contexts, and studies on deaf readers of non-alphabetic systems, such as Chinese, are still few. To our knowledge, no studies have examined how orthographic, phonological, and contextual information affect foveal word processing during Chinese reading, and how this information might be processed differently by readers with different levels of reading fluency. In the present study, we aim to investigate these questions using an error disruption paradigm.

3.1.1 Models of reading

The dual-route model (Coltheart et al., 2001; Coltheart, 2005, 2006) aims to explicate the roles of orthography and phonology in achieving lexical access during reading. An underlying assumption of this model is that we store information about words in three separate mental systems: the orthographic lexicon, which contains information about the visual forms of words; the phonological lexicon, which contains information about words’

pronunciations; and the semantic system, which contains information about the meanings of words. When reading, the semantic system can be accessed directly through orthography or indirectly, whereby orthography activates a word’s phonological representation, which then activates its meaning. The direct route from orthography to meaning is the most efficient and predominant in skilled reading. For alphabetic languages, there is a third route for grapheme-to-phoneme mapping processes used when sounding out new and unfamiliar words. A related model is the parallel distributed processing model of visual word recognition (Seidenberg & McClelland, 1989). Like the dual-route model, this model assumes that semantic representations are predominantly activated directly via orthography in skilled reading, but phonological codes automatically receive activation in parallel. Thus, according to this model, phonology can be activated pre-lexically and even influence processing during reading, while at the same time not necessarily being used to access the semantic system.

To address the question of how the cognitive processes involved in reading might differ between deaf and hearing readers, Elliott et al. (2012) proposed the dual-route cascaded model of reading by deaf adults. According to this model, which retains the cognitive structure of the dual-route model, deaf readers’ representations of the sub-lexical structure of oral language are based on mouth shapes or visual phonemes called “visemes.” To illustrate the concept of a viseme as it relates to deaf signers, we can look at an example of a viseme used by signers of Hong Kong Sign Language (HKSL), the primary language of participants in the current study. In Figure 3.1a (below), we see the sign for SELF, which translates to the Cantonese word 自己 /zi6 gei2/¹ [self], and in Figure 3.1b we see the sign for PRIVATE, which translates to 私人 /si1 jan4/ [private]. Many signers produce these along with a mouthing associated with the pronunciations of the first characters of the signs’ Cantonese translations, /zi6/ and /si1/ respectively. While the Cantonese pronunciations of these characters differ in onset and tone, they are visually indistinguishable when mouthed in signed discourse. Thus, we could argue

¹Chinese pronunciations shown in the Cantonese romanization system, Jyutping.

a) 自己 /zi6 gei2/ [self]
SELF



b) 私人 /si1 jan4/ [private]
PRIVATE

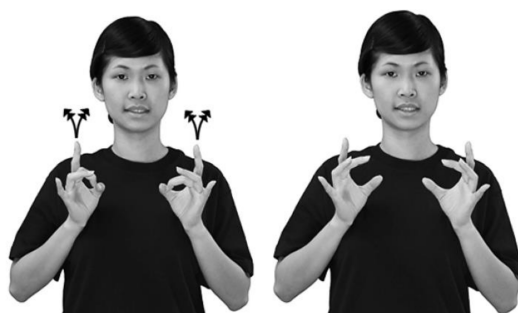


Figure 3.1: *HKSL signs with visemic mouthings*. Images of two signers of HKSL demonstrating the signs SELF (3.1a) and PRIVATE (3.1b) while co-articulating the /I/ viseme.

that the mouthings used by signers when producing these two signs are associated with a single viseme /I/, which we can see being articulated by the deaf signers in Figures 3.1a and 3.1b.

As for the role of visemes in reading, Elliott et al. (2012) proposed that when deaf readers utilize the indirect phonological route during reading, they are using visemic representations to access the semantic system rather than sound-based phonological ones. An alternative possibility is that deaf individuals use representations that include tactile information such as voicing or aspiration, which would be more detailed representations than purely visemic ones. To investigate this, Elliott et al. (2012) carried out a lex-

ical decision task with deaf readers of German that incorporated pseudo-homovisemes (e.g., *prain* as a pseudo-homoviseme for *brain* in English). They designed the pseudo-homovisemes such that they had similar mouth-shapes to real words if pronounced aloud but spellings different from any real word. They found that participants took longer to respond to pseudo-homovisemes than spelling controls, suggesting that these pseudo-words activated actual word meanings while spelling controls did not. They suggested that this model could broadly account for deaf readers of non-alphabetic languages as well—for example, Chinese characters, which represent whole syllables, would be associated with visemic-syllabic representations. However, whether this model applies to deaf readers of Chinese has not previously been tested.

3.1.2 The Chinese writing system

In describing the dual-route model of reading, we mentioned that alphabetic languages (in contrast to logographic languages such as Chinese) allow for a third, grapheme-to-phoneme mapping route in the model’s cognitive architecture. This third route does not exist in Chinese because characters in the Chinese writing system represent full morphemes and cannot be broken down into phonemic units as, for example, an English word can. To illustrate, in English, we can divide the word *mom* into three phonemes: /m/, /ʊ/, and /m/. The Chinese character 媽 /maa1/ [mother], however, can be divided into only two components: 女 /nei5/ [woman] and 馬 /maa5/ [horse]. The former is a semantic component (or “semantic radical”), which represents an aspect of the whole character’s meaning, and the latter is a phonetic component (or “phonetic radical”), which might give an idea of character’s pronunciation. Importantly, nothing in the character 媽 /maa1/ [mother] can be said to correspond to the individual phonemes /m/ and /a:/. Rather, the character maps to the syllable as a whole. While many Chinese characters contain semantic or phonetic radicals that give cues as to their meaning and pronunciation, these cues are generally unreliable as relatively few characters have phonetic or semantic radicals that correspond closely to the pronunciation and meaning of

the character (Gao et al., 1993). Chinese also contains many homophonic characters which can be unrelated in terms of their orthography. For example, the characters 清 /cing1/ [clear] and 稱 /cing1/ [call] are identical in pronunciation but contain entirely different components. In light of these different properties of Chinese and alphabetic languages like English, C. A. Perfetti et al. (1992) as well as C. A. Perfetti et al. (2005) have argued that reading processes across these orthographic systems diverge mainly in the level at which phonological activation can begin. In English, it can begin at the level of individual phonemes, while in Chinese, phonology can only be activated at the syllable level.

3.1.3 Error disruption paradigm studies

The error disruption paradigm, or homophone error paradigm, has been used to examine the roles of the orthographic and phonological processing routes during sentence reading in English (e.g., Daneman & Reingold, 2000, Jared & O'Donnell, 2017, Rayner et al., 1998) and Chinese (e.g., Feng et al., 2001, Wong & Chen, 1999, Zhou et al., 2018). In this paradigm, participants read sentences containing word or character errors while an eye-tracker records their eye-movements. Chinese sentence reading studies following this paradigm have commonly included at least four conditions, each of which involves a manipulation of the first character of a two-character word. These conditions include: a correct character condition (e.g., 自 /zi6/ [self] in 自己 /zi6 gei2/ [oneself]), an orthographic error condition (e.g., 目 /muk6/ [eye], orthographically similar but differs in pronunciation to the correct target), a homophonic error condition (e.g., 字 /zi6/ [word], which has the same pronunciation as the correct target but is orthographically dissimilar), and an unrelated error condition (e.g., 亦 /jik6/ [also], which differs from the correct target in terms of both pronunciation and orthography). Shorter fixations on orthographic or homophone errors relative to unrelated controls are taken as evidence of lexical access via orthographic or phonological activation, respectively.

Commonly used eye-fixation measures include first fixation duration (FFD), gaze du-

ration (GD), and total reading time (TRT)—all measured in milliseconds. FFD (the length of time of the first fixation on the target word) and GD (the first fixation duration plus any additional fixations before reader moves to the next word) are both considered to be an index of how easily a word is retrieved from the lexicon (Rayner, 1998, 2009). However, some researchers have argued that GDs are more reflective of semantic integration processes than FFD (Carpenter & Daneman, 1981; Inhoff, 1984). TRT is calculated as GD plus any additional fixations that occur during rereading and is considered a measure of late processing, capturing both the initial retrieval and later integration of lexical items (Conklin et al., 2018) as well as error recovery processes (Daneman & Reingold, 1993).

An early error disruption study was conducted with Cantonese-speaking readers of Traditional Chinese² by Wong and Chen (1999). The researchers manipulated the first characters of two-character target words, which were embedded in short passages to be read by participants during the experiment. Character error conditions included orthographic, homophonic, and characters that were similar in orthography but also identical in pronunciation to correct targets. In FFD, reading times were shorter only on orthographic errors relative to unrelated errors, and in GD, they found a strong effect of orthographic relatedness and a weak effect of phonological relatedness (i.e., significant across items but not subjects). In the late measure of TRT, both orthographic and phonological effects were significant, suggesting that phonological activation facilitated semantic access in late processing. According to the authors, these findings suggest a dominant role for orthography in the early stages of processing in Chinese reading, and they suggest that the activation of phonological representations occurs primarily during later stages of processing, such as when rereading for error recovery.

In a comparative study of English and Chinese reading following the same paradigm, Feng et al. (2001) found evidence only for late phonological activation among Chinese readers. For readers of English, they found evidence of very early phonological activa-

²Traditional Chinese characters are those standard in Taiwan, Hong Kong, and Macau while simplified characters are those used in Mainland China.

tion in FFD when the homophone error was both orthographically similar to the correct target and presented in a context where the target was highly predictable. These results suggested that certain variables, such as predictability, frequency, and orthographic similarity, can facilitate early phonological activation in English. However, phonological activation in Chinese only occurred in late processing regardless of how these variables were manipulated. The authors conclude that this pattern of findings suggested that Chinese readers have a stronger tendency than English readers to activate word meanings from orthographic representations. While studies on adult readers of Chinese have found only late phonological activation, developing readers of Chinese have been found to activate phonological representations in early processing. A study on Chinese reading by Zhou et al. (2018) found that children (mean age = 9.1, $SD = 0.3$) fixated on homophonic errors for shorter durations than controls in the early measure of GD and had weaker orthographic and phonological recovery skills in late measures when compared to adults.

Jared and O'Donnell (2017) suggested that the ability to quickly resolve and reintegrate errors into text, as is required of readers during the error disruption paradigm, is dependent on readers having high-quality lexical representations. High-quality lexical representations, as proposed by C. A. Perfetti and Hart (2002) in explicating the lexical quality hypothesis, consist of clearly delineated orthographic, phonological, and semantic representations that can all be activated more or less simultaneously. Lexical quality develops with repeated exposure to words, and skilled readers' lexicons primarily consist of higher quality lexical items. When skilled readers encounter an orthographic or homophonic error, they can quickly activate the target lexical item and integrate it into the meaning of the sentence based on features common to both the error and the correct target. For less-skilled readers with low-quality representations, this process is slower, more laborious, and more likely to result in poor comprehension (C. Perfetti, 2007).

3.1.4 Parafoveal preview studies with deaf readers

In contrast to the error disruption studies described in the previous section, which look at foveal processing effects, researchers have used the parafoveal preview paradigm, or boundary paradigm (Rayner, 1975), to investigate parafoveal effects, which emerge before the target is directly fixated (for an overview, see: Schotter et al., 2012, Vasilev & Angele, 2017). When reading, we do not only process the word on which we are currently fixating but also one to two words beyond it, which are within our parafoveal range of vision. After we process a word parafoveally, we can subsequently spend less time fixating directly on that word. This processing benefit gained from previewing the upcoming word in the parafovea is referred to as preview benefit.

Some researchers have used the parafoveal preview paradigm to investigate orthographic and phonological processing in Chinese (e.g., Tsai et al., 2012, Tsai et al., 2004, M. Yan et al., 2009) and English (e.g., Chace et al., 2005, Pollatsek et al., 1992, Pollatsek et al., 2000a). In these experiments, participants read sentences in which correct target words are replaced with a homophonic or orthographically-related substitute. This substitute word (or “preview”) is only visible before the readers’ eyes move from the pre-target word region to the target. As the readers’ eyes move to fixate on the target, they cross an invisible boundary that, when detected by the eye-tracking system, triggers the homophonic or orthographically-related preview to be replaced by the correct target. While readers are often unaware that the word has changed, because this change occurs while the eyes are in motion, the content of the preview word still affects subsequent processing. For example, in a study on Chinese, Tsai et al. (2012) found that fixations on correct targets are shorter when previews are orthographically-related than when previews are unrelated to correct targets.

Two relevant studies have used the parafoveal preview paradigm to investigate deaf reading. Bélanger et al. (2013) carried out a study to look at how the processing of orthographic and homophonic previews affect processing in skilled hearing, skilled deaf, and less-skilled deaf readers of English. They found phonological preview benefit among

skilled hearing readers in FFD. In contrast, both skilled and less-skilled deaf readers showed consistent orthographic benefit in FFD and GD but no overall phonological benefit in either measure, suggesting that the use of phonological code is not necessarily a characteristic of skilled deaf reading. They also found that skilled deaf readers skipped targets more often and re-fixated upon them less frequently than hearing readers, which they suggested was evidence of deaf readers having more efficient parafoveal processing resulting from a wider perceptual span.

M. Yan et al. (2015) conducted a Chinese parafoveal preview experiment with deaf and hearing readers in Beijing, China. Their experiment included a semantic preview condition (a contextually incorrect character that is similar in meaning but different from the correct target in pronunciation and orthography) in addition to orthographic, homophonic, and unrelated conditions. They found an early preview benefit of semantically related characters for deaf readers in FFD which became preview cost (i.e., longer reading times relative to the unrelated error control) in the late measures of go-past time and TRT, suggesting that competition between the overlapping semantics of the character processed parafoveally and the correct target character led to an inhibitive processing effect. For hearing readers, a beneficial effect of semantic previews was found but only in later measures of TRT and go-past time. The authors concluded that the very early effects of semantic previews suggest that deaf readers' parafoveal processing is more efficient, similar to the deaf English readers in Bélanger and Rayner (2013). They found no overall effect of homophonic previews. However, there was some evidence of homophonic preview benefit in GD when preview durations were longer and reading level was higher, suggesting that phonological extraction in Chinese requires longer preview durations and that phonological effects might relate to reading level in deaf readers. The authors proposed that familiarity with Hanyu Pinyin (the Chinese romanization³ system used to represent the Mandarin Chinese pronunciations of Chinese characters) might be facilitating phonological activation.

³Hong Kong schools have not traditionally used a Cantonese romanization system to teach the pronunciations of traditional Chinese characters (C. S.-H. Ho & Bryant, 1997b).

3.1.5 Contextual predictability

Eye-tracking studies on hearing readers of English and Chinese have found that the predictability of target words affects the length of time readers fixate on them (Rayner & Well, 1996; Sereno et al., 2017; G. Yan et al., 2006). These studies found that readers' fixations on low-predictable targets were significantly longer than medium- and high-predictable targets. However, there was no significant difference between fixation times on medium- and high-predictable targets, suggesting moderate and high levels of predictability facilitate lexical access to similar degrees. Some studies have found that lexical access in advanced readers is less facilitated by contextual predictability than it is in average or less-skilled readers (Ashby et al., 2005; Slattery & Yates, 2018). However, the evidence for this is mixed, and some research has found predictability effects to be similar across readers of different skill levels (Steen-Baker et al., 2017; Whitford & Titone, 2014). An eye-tracking study by Bélanger and Rayner (2013) found that both skilled deaf and skilled hearing readers fixated on targets for longer durations when they were in neutral sentence contexts than when they were in predictable contexts. Gaze durations of less-skilled deaf readers indicated that they were more strongly affected by predictability than skilled deaf readers.

Contextual predictability is also an important factor related to phonological activation in the error disruption paradigm. In one study on English reading, Rayner et al. (1998) found that when a target word was highly predictable based on context (e.g., *brake* in “to avoid a car crash, she slammed on the *brake*”), evidence of phonological activation was more likely to emerge in early processing measures. Daneman and Reingold (2000) posited that these early phonological effects, found in English when target words are highly predictable from the preceding sentence context, result from top-down processes by which a word's phonological representation is activated by semantics rather than by the text itself.

While this effect was not found for Chinese when investigated by Feng et al. (2001), Thierfelder, Durantin, et al. (2020) reexamined this issue in an error disruption study

with Cantonese-speaking readers of Chinese. Overall patterns of activation showed early, dominant effects of orthography in FFD and GD, with evidence of only late phonological activation in TRT. However, there was a significant interaction between the predictability values associated with each sentence and the homophonic condition in GD and TRT, which suggested that earlier phonological activation can be facilitated in contexts with high predictability targets and allows readers to more quickly resolve homophone errors and integrate the target meanings into the sentence. This study extended the findings of Daneman and Reingold (2000) and Rayner et al.'s (1998) studies on English reading and showed that top-down processes could play a role in facilitating phonological activation during Chinese reading as well.

3.2 The present study

Past studies on the roles orthographic and phonological code during Chinese sentence reading by deaf readers have mainly focused on parafoveal processing. To our knowledge, none have investigated foveal processing effects, which would bring the advantage of allowing us to examine error recovery processes, not only during early fixations but during rereading as well. Thus, the present study employs an error disruption paradigm to examine how orthographic and phonological information are used by deaf readers when resolving orthographic, homophonic, and homovisemic errors. Furthermore, we include the predictability levels of target stimuli and participants' reading fluency levels in our analysis to examine how these factors affect orthographic and phonological coding processes during reading.

Beyond an interest in whether phonological activation occurs in deaf readers, we are also interested in better understanding the nature of the phonological units that deaf readers might possess in their mental lexicons. Including a homovisemic condition allows us to test Elliott et al.'s (2012) model of reading for deaf adults by investigating whether or not deaf readers activate visemic representations. Furthermore, as the deaf

participants in the present study previously attended deaf schools in Hong Kong that did not teach Cantonese romanization, activation of phonological units based on Cantonese romanization is highly unlikely. Thus, we predict that if skilled deaf readers do show phonological effects, as they did in M. Yan et al. (2015), we would see evidence that those representations were based on mouth shape, as predicted by Elliott et al. (2012) dual-route cascaded model of reading by deaf adults.

3.3 Method

3.3.1 Participants and background measures

Thirty-one participants with severe to profound hearing loss (between 80 and 120 dB in our sample; $M = 102$, $SD = 11$) took part in the experiment. All had attended oral deaf schools, where instruction was in spoken Cantonese, from a young age, and had graduated from high school. All deaf participants reported being daily users of HKSL, which is a natural sign language distinct from Cantonese and written Chinese in terms of lexicon and syntax (Tang, 2007). The mean age of deaf participants was 37 years old ($SD = 6$)⁴.

While practical constraints at the time of the study prevented us from recruiting a well-matched hearing comparison group, we included an unmatched sample of 30 hearing participants to serve as a point of reference. These hearing participants were native speakers of Cantonese from a university in Hong Kong and had a mean age of 19 ($SD = 2$) years old. All reported that they had never learned any sign language in the past. All participants took a Chinese reading fluency test modeled after those described in Moll et al. (2009) and Pan et al. (2011). The test contained a total of 85 sentences, which progress in length from 9 characters at the beginning of the test to 20 characters by the end. Among these sentences, 29 contained obvious semantic or grammatical errors.

⁴The signing deaf population of Hong Kong skews older as mainstream education has become dominant and only one school for the deaf remains (Sze et al., 2013)

Participants were asked to read as many sentences as they could in two minutes while marking each sentence as correct or incorrect. Fluency scores for each participant were calculated as the sum of characters contained in the correctly judged sentences. Reading fluency tests indicated that deaf participants read at an average rate of about 146 ($SD = 49$) characters per minute. Deaf reading fluency scores were significantly lower than those of the hearing participants ($p < .001$), who read at an average of 259 ($SD = 91$) characters per minute. All participants had normal or corrected-to-normal vision.

Ethical clearance was attained from the authors' universities, and participants gave written consent before participation. In addition to providing all information in written Chinese, explanations of consent forms and study procedures were provided to deaf participants in HKSL by a fluent signer.

3.3.2 Materials

Stimuli were adapted from Thierfelder, Durantin, et al. (2020). To construct these stimuli, twenty sets of traditional Chinese characters were selected, each set containing a correct character (e.g., 上 /soeng6/ [above] in 上帝 /soeng6 dai3/ [God]), an orthographically similar character (e.g., 止 /zi2/ [stop]), a homophonic character (e.g., 尚 /soeng6/ [esteem]), a homovisemic character (e.g., 丈 /zoeng6/ [husband]—this condition is explained in more detail below) and an unrelated control character (e.g., 以 /ji5/ [with]). Correct targets were not semantically related to their corresponding substitutions. To verify this, we calculated the semantic relatedness between characters using HowNet (Dong et al., 2006), which is a Chinese semantic database for natural language processing that has been shown to produce similarity ratings that closely reflect human judgments (Dai et al., 2008). Semantic relatedness between correct targets and substitution characters was low overall ($M = .27$, $SD = .28$). Analysis of variance showed that there were no significant differences in semantic relatedness across conditions [$F(3, 74) = 1.59$, $p > .1$]. Orthographic, homophonic, homovisemic, and unrelated characters were matched where-

ever possible with the correct character for strokes ($M = 6.6$, $SD = 2.5$) and frequency⁵ ($M = 167$, $SD = 120$). There was no effect of condition for either [number of strokes: $F(4, 93) = 0.58$, $p > .1$; frequency: $F(4, 93) = 1.94$, $p > .1$].

Sets did not include any phonograms (i.e., characters that contain a phonetic radical on the right side, such as 情 /cing4/ which has the phonetic radical 青 /cing1/), which might have different effects on phonological processing than non-phonograms (Pollatsek et al., 2000b). Homovisemic characters were characters pronounced with mouth-shapes that are indistinguishable (or near-indistinguishable) from the correct targets (an analogous example in English would be mom and bomb). Seventeen out of 20 homovisemic characters had the same rime as the correct targets and differed in onset (e.g., 自 /zi6/ [self] and 示 /si6/ [announce]), and onsets differed in ways that were not visually salient (for example, in voicing or aspiration). Three pairs did not overlap in rime but contained the same vowels and were pronounced with highly similar mouth-shapes (e.g., 各 /gok3/ [every] and 哥 /go1/ [elder brother]), particularly when produced by signers during signed discourse, in which signers tend to utilize reduced mouthings (Siu, 2007). We calculated the average proportion of phonemes shared by correct characters and related conditions based on their associated Cantonese Jyutping romanizations. Homophones share 100% phonemic overlap entirely with correct characters, while homovisemic errors share an average 65% ($SD = 15\%$) of their phonemes with correct targets. Orthographic and unrelated characters share on average only 12% ($SD = 18\%$) and 23% ($SD = 25\%$), respectively, of their phonemes with correct characters.

Characters in the orthographic condition differed from the corresponding correct targets by no more than two strokes. To confirm that readers would perceive the orthographic matches we selected to be similar in appearance to the correct target characters, we conducted a norming study with twenty native Cantonese speaking participants who did not take part in the experiment. We asked these participants to judge how similar in appearance the orthographic, homophonic, homovisemic, and unrelated characters were

⁵Frequencies were calculated using the average token count per corpus entry from (H. H. Ho & Kwan, 2001).

to the correct targets on a scale of one (highly dissimilar) to five (highly similar). As intended, there was a significant effect of condition on orthographic similarity [$F(1, 20) = 108.91, p < .001$]. Pairwise comparisons revealed that the orthographically similar characters ($M = 3.6, SD = 1.2$) were rated as significantly ($ps < .001$) more similar to targets than homophonic ($M = 1.3, SD = 0.6$), homovisemic ($M = 1.3, SD = 0.6$), and unrelated characters ($M = 1.3, SD = 0.6$) while neither homophonic nor homovisemic characters differed significantly with unrelated characters in their overall similarity rating (both $ps > .1$). All character properties are summarized in Table 3.1.

	Correct	Orthographic	Homophonic	Homovisemic	Unrelated
	上	止	尚	丈	以
Example	/soeng6/ [above]	/zi2/ [stop]	/soeng6/ [esteem]	/zoeng6/ [husband]	/ji5/ [with]
Frequency	214 (135)	125 (136)	135 (111)	177 (144)	183 (132)
Orthographic Rating	–	3.6 (1.2)	1.3 (0.6)	1.3 (0.6)	1.3 (0.6)
Phonemic Overlap	–	.12 (.18)	1 (0)	.65 (.15)	.23 (.25)
Semantic Relatedness	–	.30 (.37)	.20 (.17)	.20 (.28)	.36 (.35)
Stroke Count	6.3 (2.8)	6.4 (2.2)	7.4 (2.7)	6.7 (3.0)	6.5 (3.0)

Table 3.1: *Character properties*. *SDs* in parentheses. Mean frequencies from H. H. Ho and Kwan’s (2001) Hong Kong corpus. Semantic similarity calculated using the HowNet (Dong et al., 2006) database.

To confirm that the deaf participants were familiar with the pronunciations of the characters, they were asked to mouth or pronounce each one after participating in the experiment. Trials associated with one character from the homophonic condition and one from the homovisemic condition were removed as around 50% of the deaf participants were unfamiliar with them. Because there are a limited number of traditional Chinese character pairs that are highly similar in orthography, we included four less-common characters—for example, 戍 /syu3/ [garrison] as the orthographically similar mate to 成 /sing4/ [succeed]. Most deaf participants did not know the pronunciations of these characters. However, trials associated with these characters were retained in the final statistical analysis after we confirmed, by running a second statistical analysis that excluded these trials, that these characters did not affect significance patterns (presumably because

participants were still able to easily resolve them based on their visual similarity to the correct targets).

Each target character was embedded as the first character in a set of three to five different two-character word frames—for example, 成 [accomplish] was embedded in 成功 [succeed], 成績 [result], 成熟 [mature], 成為 [become] and 成員 [member]. Eye-fixation measures were based on fixations within these two-character word regions (following Feng et al., 2001, Wong & Chen, 1999, Zhou et al., 2018). Most words were selected from the Hong Kong Primary School Vocabulary Learning List (Chan, 2007) to ensure that both groups of participants could easily recognize them. When correct characters were replaced with any of the substitution conditions, the resulting two-character pair never formed a legal word. Target words were embedded in one-hundred different sentence frames, all 20–25 characters in length, which were collected from online sources. Target words appeared two or more words from the beginning of the sentence or any punctuation marks such as a period or comma. A within-items design was used such that the second character of the target word, as well as the sentence frames, were identical across conditions. In the end, there were five stimulus lists, each containing the same 100 sentence frames. Within each list, there were 20 correct sentences, 20 with an orthographic error, 20 with a homophonic error, 20 with a homovisemic error, and 20 with an unrelated character error. The pairing of sentence frames and targets was counterbalanced across lists so that no participant was exposed to the same sentence frame or target character more than once. Table 3.2 shows an example sentence in the five different conditions. Out of concern that some participants, particularly the less proficient readers, might experience reading fatigue as the experiment progressed, we did not include any filler sentences as doing so would have considerably extended the experiment’s length.

To incorporate contextual predictability as a variable in our study, we used a design modeled after Daneman and Reingold (2000) and Rayner et al. (1998), which required us to ascertain how predictable target words were in each sentence frame. To do this, we conducted a norming study using the cloze procedure (Taylor, 1953) with an independent

Condition	Sentence
Correct character 自然 /zi6 jin4/ [nature]	環保主義者要求政府保護 <u>自然</u> 環境和瀕臨滅絕的動物. “Environmentalists demand that the government protect the natural environment and endangered animals.”
Orthographic error 目然 /muk6/ + /jin4/ [eye]+[correct]	環保主義者要求政府保護 <u>目然</u> 環境和瀕臨滅絕的動物.
Homophonic error 字然 /zi6/ + /jin4/ [word]+[correct]	環保主義者要求政府保護 <u>字然</u> 環境和瀕臨滅絕的動物.
Homovisemic error 示然 /si6/ + /jin4/ [show]+[correct]	環保主義者要求政府保護 <u>示然</u> 環境和瀕臨滅絕的動物.
Unrelated error 分然 /fan1/ + /jin4/ [divide]+[correct]	環保主義者要求政府保護 <u>分然</u> 環境和瀕臨滅絕的動物.

Table 3.2: *Set of example sentences.* A set of example sentences used across the five item lists in the experiment. Target words are underlined for clarity.

sample of 20 participants who did not take part in our experiment. These participants were presented with each sentence frame up to but not including the target word and allowed one open-ended guess as to what the next word would be. The proportion of correct guesses for each sentence frame was used as the predictability values in our statistical analysis. Predictability values ranged from 0 (no correct guesses) to .95 (the target character was correctly guessed about 95 percent of the time, or by 19 out of 20 participants). The mean predictability of targets across all sentence frames was .21 ($SD = .26$). Predictability values did not correlate with sentence length, target frequency, or target stroke count ($ps > .1$). Table 3.3 shows four different example sentences and their respective predictability values.

Predictability Value	Sentence
.95	新法例可能會扼殺我們的言論 <u>自由</u> 以及藝術創作的權利. “This new law might suppress our <u>freedom</u> of speech (lit. speech-freedom) and right of expression.”
.65	四年前, 阿明以優異的學習 <u>成績</u> 畢業於哈佛大學. “Four years ago, A-ming graduated from university with exceptional <u>grades</u> .”
.3	家人不在時, 他根本不會照顧 <u>自己</u> 或者獨立生活. “When his family is absent, he cannot take care of <u>himself</u> or live independently.”
0	工作時, 工作人員不太喜歡 <u>上司</u> 整天監督他們做事的方法. “At work, employees don’t really like when their <u>boss</u> micro-manages them.”

Table 3.3: *Set of example sentences and corresponding predictability values.* A set of example sentences with different predictability values. Target words are underlined. The sentence with a .95 predictability value has the most predictable target word while the sentence with a 0 predictability value has the least predictable target word.

3.3.3 Apparatus

Eye-movements were recorded using an Eyelink 1000 Plus desktop system running at 1000 Hz. The experiment was run on a Dell Optiplex 7020 PC (processor: Intel Core i7-4790 running at 3.6 GHz; operating system: Windows 7) with a ViewSonic XG2402 24-inch monitor (resolution: 1920×1080 ; refresh rate: 144 Hz). Participants were seated 60 cm away from the monitor. Stimuli were single-line sentences presented in the center of the screen. The Chinese text was displayed in black on white using the font KaiTi, size 36. Each character equaled 1.4° of visual angle.

3.3.4 Procedure

Each participant performed a 5-point calibration and validation of the eye-tracker before beginning the experiment and at the beginning of the second block. Drift correction was performed before each sentence. Calibration and validation were repeated if drift correction error exceeded 1° of visual angle. Participants were instructed to read for

comprehension and not to be concerned about any errors they might encounter. While error disruption paradigm experiments usually include a limited number of comprehension questions to encourage participants to read for meaning, we avoided this due to concern that some participants might spend excessive amounts of time trying to decipher character errors and remember the sentence. Instead, we asked participants to simply indicate whether they felt they understood each sentence by pressing designated yes-no keys on the keyboard. These responses were unrecorded as they were not intended for analysis, and the task was only used to encourage active reading. Sentences were presented in random order. Participants were given a chance to rest after 50 sentences, after which calibration and validation were performed again. A practice block of five sentences was done at the beginning of the experiment to ensure that all participants were familiar with the experimental procedure. Each experimental session lasted around 40 minutes.

3.3.5 Data analysis

Inferential statistics were based on planned comparisons of the correct, orthographic error, homophonic error, and homovisemic error conditions with the unrelated error condition, which served as the reference level in all our models. Our analyses of fixation times included three dependent variables: FFD (the length of the first fixation on the target), GD (the sum of the first fixation in addition to any subsequent fixations on the target word before moving to the next word), and TRT (the sum of all fixations on the target including regressive fixations). To check for evidence of visemic activation, we carried out an additional post hoc comparison when both homophonic and homovisemic conditions produced significant effects. A significant difference between these two conditions was taken as evidence that participants were activating sound-based or detailed visual-tactile phonological representations, and a lack of significant difference between the homophonic and homovisemic conditions was taken as evidence that participants were activating the same underlying phonological representations (i.e., viseme-based representations).

Fixation times for 5% of the total number of trials were not recorded due to skipping,

movements, blinks, or machine failure. Observations with FFDs under 60 ms or GDs more than 1200 ms were discarded for deaf and hearing participant groups (deaf: 4% percent of data; hearing: 4% of data). After filtering, 2676 observations remained of each dependent variable for the hearing participants (91% of trials), and 2766 observations remained for the deaf participants (91% of trials).

Linear mixed models (LMMs) are widely used to analyze reaction and fixation time data in psycholinguistic studies. This data is almost always positively skewed, and LMM guidelines recommend applying a log-transformation to satisfy assumptions of normality and homoscedasticity (Baayen, 2008). However, applying non-linear transformations to skewed data changes the shape of the distribution, and it can lead to a loss of valuable information about mental chronometry, such as the degrees of impact different conditions have on processing time in terms of milliseconds. Lo and Andrews (2015) argued that untransformed data is ideal for studies of mental chronometry and recommended the use of generalized linear mixed models (GLMMs), which can accommodate the shape of skewed data distributions. Following the approach described by Lo and Andrews (2015), we used a Gamma distribution with an identity link between the predictors and dependent variables to avoid log-transforming our fixation time data. Models were built for each dependent variable in R (Team, 2014) using the lme4 package (Bates et al., 2012).

The best approach to random effects structures in mixed models is currently a debated issue. Barr et al. (2013) have recommended fitting models with maximal random-effects structures while Bates et al. (2015) and Matuschek et al. (2017) have argued that reducing models can increase statistical power without necessarily increasing the Type I error rate. In our models, the inclusion of random slopes led to convergence failures even when models were reduced to only one fixed and one random effect, which suggests that random slopes models were too complex to be supported by our data set. Using the Akaike information criterion (AIC; Akaike, 1998) to evaluate random effects structures, models with by-participant and by-item (i.e., sentence frame) random intercepts were determined to fit the data best.

To examine the effects of context and reading level on error recovery processes among the deaf readers, predictability values and reading test scores were included as fixed effects. Both were analyzed as continuous variables to avoid problems associated with dichotomization (MacCallum et al., 2002). Full models for deaf participants were specified as follows: (Eye-Tracking Measure) $\sim$ Condition $\times$ Predictability Value $\times$ Reading Test Score + (1 | Participant) + (1 | Item). Models for hearing participants excluded reading fluency scores as this variable did not interact with any of the experimental conditions for that group and did not improve model fit [formula: (Eye-Tracking Measure) $\sim$ Condition $\times$ Predictability Value + (1 | Participant) + (1 | Item)]. Continuous predictors were centered and scaled.

Absolute t -values at or above 1.96 indicate statistical significance at the 0.05 alpha level. For conciseness, we report the main effects of predictability, reading fluency, and trial number only when they interacted significantly with one of the experimental conditions. Full summaries of means (computed over participants' means) from the raw data are presented for each fixation measure for the hearing readers in Table 3.4 and for the deaf readers in Table 3.5. The first set of GLMMs, used in the main analysis, can be found in Appendix 2 in Table 6.5 for the hearing readers and in Table 6.62 for the deaf readers.

3.4 Results

3.4.1 Hearing readers

Overall orthographic and phonological effects

In FFD (Figure 3.2a), fixations were significantly shorter in the correct condition than in the unrelated condition ($b = -41.50$, $SE = 4.39$, $t = -9.45$), but there were no significant differences between unrelated errors and other error types (orthographic: $b = -2.65$, $SE = 4.63$, $t = -0.57$; homophonic: $b = -0.19$, $SE = 4.79$, $t = -0.04$; homovisemic: b

$= 1.23$, $SE = 4.65$, $t = 0.26$). In GD (Figure 3.3a), fixations in both correct ($b = -152.03$, $SE = 5.37$, $t = -28.32$) and orthographic ($b = -33.43$; $SE = 6.03$; $t = -5.54$) conditions were significantly shorter than in the unrelated condition, indicating that hearing readers resolved orthographic errors more quickly than unrelated errors. There were no significant differences between the phonologically related conditions and unrelated conditions (homophonic: $b = -8.70$, $SE = 6.23$, $t = -1.40$; homovisemic: $b = -10.23$, $SE = 6.52$, $t = -1.57$). In TRT (Figure 3.4a), fixations were significantly shorter in the correct ($b = -871.33$, $SE = 40.21$, $t = -21.67$), orthographic ($b = -524.77$, $SE = 44.34$, $t = -11.83$), homophonic ($b = -605.18$, $SE = 43.20$, $t = -14.01$), and homovisemic conditions ($b = -310.56$, $SE = 48.45$, $t = -6.41$) than in the unrelated condition, suggesting that hearing readers were activating word meanings through orthographic and phonological representations in late error recovery processes. While both homophonic and homovisemic errors were fixated for significantly shorter times (by 600 and 300 ms, respectively) than unrelated controls, an additional post hoc comparison showed that fixations on homophonic errors were significantly shorter than on homovisemic errors ($p < .001$), which indicates that full phonemic overlap (as in homophone errors) allows for quicker error recovery than partial phonemic overlap (as in homovisemic errors).

	Correct	Orthographic	Homophonic	Homovisemic	Unrelated
FFD (ms)	215 (4)	254 (5)	258 (5)	259 (5)	258 (5)
GD (ms)	251 (6)	394 (12)	411 (11)	409 (11)	423 (12)
TRT (ms)	355 (20)	880 (34)	713 (25)	1127 (43)	1459 (56)

Table 3.4: *Eye-tracking measures for hearing readers.* Means for all eye-tracking measures (FFD = first fixation duration; GD = gaze duration; TRT = total reading time) with standard errors in parentheses. Values computed across participants' means.

Predictability effects

There was a significant effect of predictability for the homophonic v. unrelated contrast ($b = -16.11$, $SE = 5.79$, $t = -2.78$), indicating that fixation times on homophonic errors became progressively shorter, relative to fixation times on unrelated errors, as the

predictability values associated with targets increased.

3.4.2 Deaf readers

Overall orthographic and phonological effects

In FFD (see Figure 3.2b), fixations were significantly shorter in the orthographic ($b = -17.89$, $SE = 5.35$, $t = -3.34$) and correct conditions ($b = -33.35$, $SE = 4.63$, $t = -7.20$) than in the unrelated condition. The orthographic effect in FFD indicates that deaf readers were activating orthographic representations in very early processing. FFDs in homophonic ($b = -9.37$, $SE = 5.13$, $t = -1.83$) and homovisemic ($b = -0.32$, $SE = 5.32$, $t = -0.06$) conditions were not significantly different than in the unrelated condition. In GD (Figure 3.3b), fixations in orthographic ($b = -35.66$, $SE = 5.83$, $t = -6.11$) and correct conditions ($b = -100.33$, $SE = 6.60$, $t = -15.20$) were significantly shorter than in the unrelated condition. However, fixation times on homophonic ($b = -5.21$, $SE = 7.00$, $t = -0.74$) and homovisemic errors ($b = -8.37$, $SE = 7.41$, $t = -1.13$) did not differ significantly from those on unrelated errors. In TRT (Figure 3.4b), fixation times were significantly shorter in correct ($b = -799.21$, $SE = 65.79$, $t = -12.15$), orthographic ($b = -423.15$, $SE = 74.28$, $t = -5.70$), homophonic ($b = -167.38$, $SE = 82.78$, $t = -2.02$), and homovisemic ($b = -178.33$, $SE = 82.17$, $t = -2.17$) conditions than in the unrelated condition, indicating that deaf readers were activating word meanings through orthographic and phonological representations in late processing. The additional post hoc comparison of homophonic and homovisemic conditions showed that fixation times in these two conditions were not significantly different from each other ($p > .1$), which suggests that phonological representations activated in TRT might be based on visemes.

	Correct	Orthographic	Homophonic	Homovisemic	Unrelated
FFD (ms)	237 (4)	259 (5)	266 (5)	266 (5)	270 (5)
GD (ms)	297 (8)	392 (11)	421 (12)	405 (11)	407 (11)
TRT (ms)	519 (33)	1091 (41)	1357 (55)	1355 (54)	1486 (72)

Table 3.5: *Eye-tracking measures for deaf readers.* Means for all eye-tracking measures (FFD = first fixation duration; GD = gaze duration; TRT = total reading time) with standard errors in parentheses. Values computed across participants' means.

Predictability effects

There was a significant effect of predictability for the contrast between the correct and unrelated conditions ($b = -10.60$, $SE = 4.89$, $t = -2.17$), indicating that FFDs became progressively shorter on correct targets relative to controls as target predictability increased. This pattern was also significant in GD ($b = -19.73$, $SE = 5.35$, $t = -3.69$). In GD, there were significant effects of predictability for both orthographic v. unrelated ($b = -15.39$, $SE = 6.12$, $t = -2.52$) and homophonic v. unrelated ($b = -12.87$, $SE = 6.47$, $t = -1.99$) contrasts, suggesting that higher contextual predictability facilitated deaf readers' lexical access when reading words with orthographic and homophonic errors. Showing the opposite trend, deaf readers' fixations on homovisemic errors were longer than those on unrelated errors when reading sentences with high predictability targets ($b = 26.11$, $SE = 6.11$, $t = 4.27$). In TRT, there was a significant effect of predictability for the contrast between the homophonic and unrelated conditions ($b = -154.72$, $SE = 75.19$, $t = -2.06$), like that found in GD.

Reading fluency effects

In FFD, we found a significant interaction between reading fluency and predictability for the contrast between the correct and unrelated conditions ($b = -15.25$, $SE = 5.79$, $t = -2.63$), which suggests that higher fluency deaf readers fixated on correct characters for shorter durations (relative to fixations on unrelated errors) than lower fluency deaf readers in high predictability sentences. In GD, the effect of reading fluency was signifi-

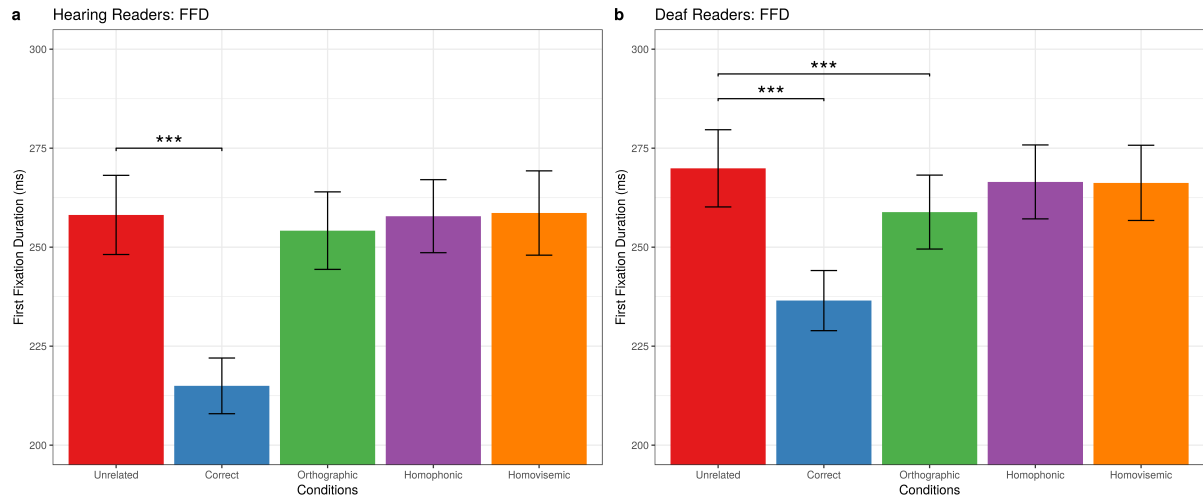


Figure 3.2: *First fixation durations for hearing and deaf readers.* Average first fixation durations (FFDs) in milliseconds for each condition. Hearing reader data shown in plot 3.2a. Deaf reader data shown in 3.2b. Stars denote level of statistical significance based on estimated p -values produced by the lmerTest package in R (Kuznetsova et al., 2017). Error bars show 95% confidence intervals.

cant for the contrast between homophonic and unrelated conditions ($b = -29.92$, $SE = 6.88$, $t = -4.35$), indicating that deaf readers' had shorter GDs on homophonic errors (relative to GDs on controls) correlating with increasing reading fluency scores. Also in GD, there were significant three-way interactions between predictability and reading fluency for homophonic v. unrelated ($b = 27.07$, $SE = 7.05$, $t = 3.84$) as well as homovisemic v. unrelated contrasts ($b = 48.02$, $SE = 6.69$, $t = 7.17$), which suggests that the disruptive effects of homophonic and homovisemic errors were greater among higher fluency readers than lower fluency readers in contexts with high predictability targets. In TRT, interactions between reading fluency and both correct v. unrelated ($b = -237.43$, $SE = 83.85$, $t = -2.83$) and orthographic v. unrelated ($b = -278.19$, $SE = 96.39$, $t = -2.89$) contrasts indicated that, in late processing, deaf readers had shorter fixation times on correct characters and orthographic errors, compared to fixation times on controls, correlating with increasing reading fluency scores.

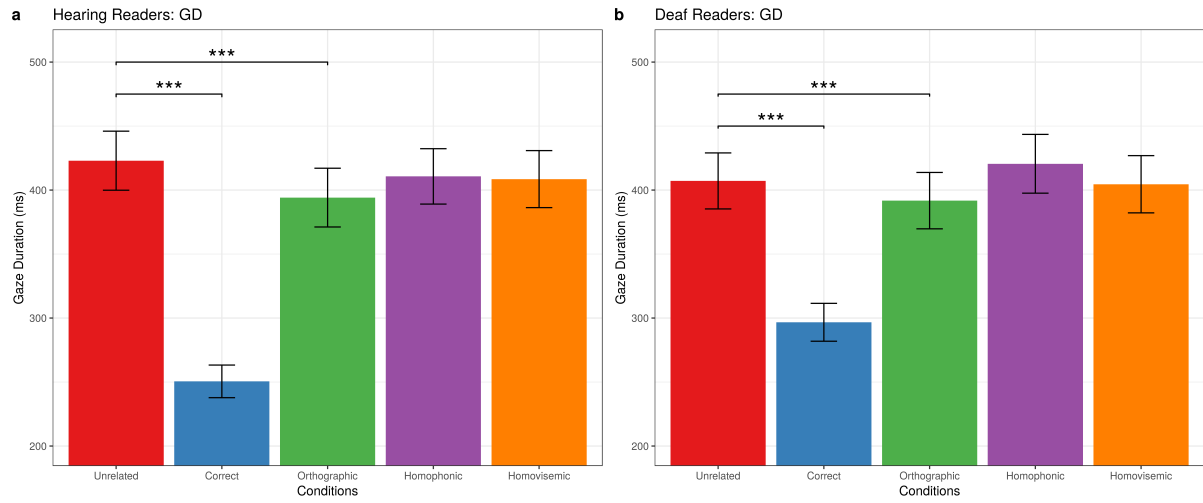


Figure 3.3: *Gaze durations for hearing and deaf readers.* Average gaze durations (GDs) in milliseconds for each condition. Hearing reader data shown in plot 3.3a. Deaf reader data shown in 3.3b. Stars denote level of statistical significance based on estimated p -values produced by the lmerTest package in R (Kuznetsova et al., 2017). Error bars show 95% confidence intervals.

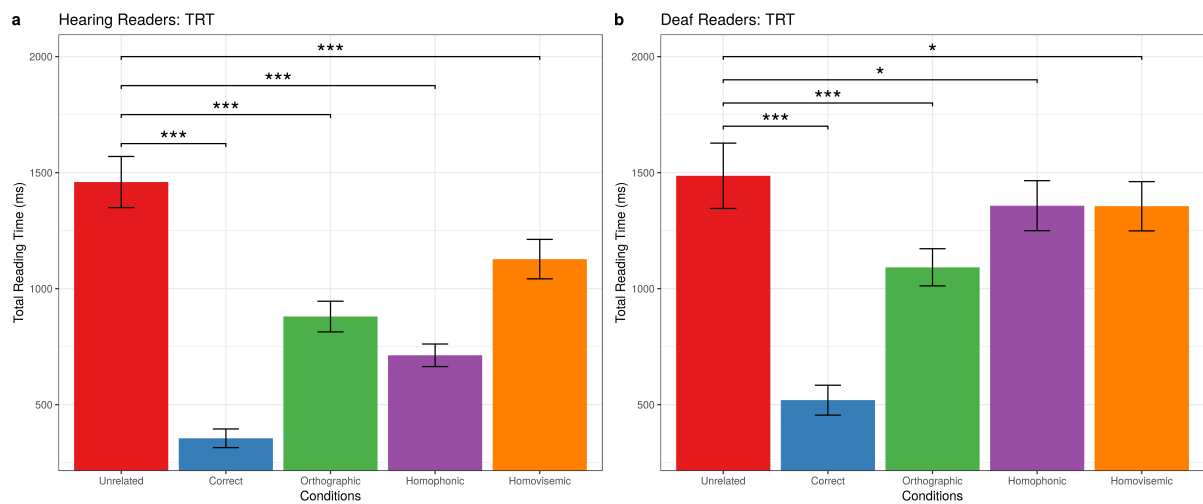


Figure 3.4: *Total reading times for hearing and deaf readers.* Average total reading times (TRTs) in milliseconds for each condition. Hearing reader data shown in plot 3.4a. Deaf reader data shown in 3.4b. Stars denote level of statistical significance based on estimated p -values produced by the lmerTest package in R (Kuznetsova et al., 2017). Error bars show 95% confidence intervals.

3.5 Discussion

In this study, we aimed to investigate the foveal processing of orthographic, homophonic, and homovisemic errors by deaf readers of Chinese and test the validity of the dual-route cascaded model of reading by deaf adults (Elliott et al., 2012) for Chinese sentence reading. To do this, we used an error disruption paradigm with five conditions: correct, orthographic, homophonic, homovisemic, and unrelated. We included two additional predictors, contextual predictability and reading fluency level, both of which have previously been found to influence phonological processing, to examine their effects on the error recovery processes of deaf readers. We conducted our experiment with two groups of participants: a group of deaf readers, to address our main research questions, and an unmatched group of hearing readers, to serve as a point of reference for discussion.

3.5.1 Hearing readers

Overall orthographic and phonological effects

Among the hearing readers, we found the expected pattern of results, which reflected the patterns found in previous error disruption studies (e.g., Feng et al., 2001, Thierfelder, Durantin, et al., 2020, Wong & Chen, 1999, Zhou et al., 2018). These readers primarily activated word meanings through orthographic representations in early processing. However, in TRT, total fixation times were significantly shorter in orthographic, homophonic, and homovisemic conditions compared to the control condition, suggesting that both orthographic and phonological representations are activated in late processing and facilitate error recovery. Homovisemic errors, which had only partial phonemic overlap with correct targets, also allowed for faster error recovery than controls, but fixation times in this condition were still significantly longer than those in the homophonic condition.

Predictability effects

We found that hearing readers’ fixations on homophonic errors became increasingly shorter relative to fixations on unrelated errors as target predictability increased in GD. This pattern of results suggests that phonological representations can receive early, top-down activation via semantics, which then facilitates readers in quickly resolving the homophonic error and integrating the target meaning into its sentential context (see discussion in Thierfelder, Durantin, et al., 2020).

3.5.2 Deaf readers

Overall orthographic and phonological effects

In our analysis of the deaf readers’ data, we found that they activated orthographic representations very early in FFD, and that word meaning were primarily activated via orthographic representations across early and late measures of processing. There was some evidence of phonological activation in late processing as TRTs were significantly shorter in the homophonic and homovisemic conditions than in the unrelated condition. However, this phonological effect was relatively weak compared to the effect of orthographic similarity. Compared to TRTs on unrelated controls, TRTs were only shorter by around 167 and 178 ms in the homophonic and homovisemic conditions, respectively, and around 423 ms shorter in the orthographic condition. In contrast, we saw that lexical access in hearing readers received much more facilitation from phonological information than it did in deaf readers—for the hearing readers, TRTs were reduced by around 605 ms for homophone errors and 311 ms for homovisemic errors relative to TRTs on unrelated errors. Fixation times in the homophonic and homovisemic conditions were not significantly different from each other among the deaf readers, which could indicate that they were using visemic representations when rereading words for error recovery. In a post hoc examination of the data, we saw that, as the deaf readers completed more trials in the experiment, their TRTs on homovisemic errors became progressively shorter relative

to their TRTs on unrelated errors, which suggests that their use of visemic code in TRT might have been part of an adaptive error recovery strategy.

Predictability effects

In GD, the effect of predictability was significant for contrasts between unrelated errors and orthographically and phonologically related error types, which suggests that context is an important factor that modulates orthographic and phonological processing in deaf readers. Importantly, the interactions between predictability and the homophonic v. unrelated and homovisemic v. unrelated contrasts indicate that deaf readers can activate phonology top-down via semantics in high predictability contexts, which is a finding in line with patterns seen among hearing readers (Daneman & Reingold, 2000; Rayner et al., 1998; Thierfelder, Durantin, et al., 2020).

Interestingly, predictability did not affect fixation times in the homophonic condition in the same way it affected fixation times in the homovisemic condition. For homophonic errors, higher contextual predictability facilitated error recovery, leading to shorter fixation times on homophonic errors than on unrelated errors. However, when homovisemic errors appeared in high predictability contexts, there was a tendency for target fixations to be longer compared to unrelated errors in the same contexts⁶. The finding of a disruptive effect of homovisemic errors in high predictability contexts might be an effect related to rhyme inhibition, such as that found by Lukatela and Turvey (1996). Based on the findings of their primed naming experiments, they concluded that rhyming primes create competition between the partially-conflicting phonological forms activated by the prime and target words, resulting in inhibitory priming effects. Erroneous characters that partially overlap with correct targets in phonology might lead to similar interference during error recovery processes. An important implication of the diverging patterns we found associated with homophonic and homovisemic errors is that they suggest that most

⁶There was also a significant effect of predictability in the control condition (see Table 6.6), indicating that controls were more disruptive in higher predictability contexts. The effects of the correct, orthographic, homophonic, and homovisemic conditions were calculated relative to this baseline interaction.

deaf readers in our study had phonological representations detailed enough to distinguish between fully homophonic characters and those that only share the same mouth shape.

Reading fluency effects

As discussed in the introduction, many deaf readers do not attain high levels of literacy, and some researchers have suggested that weak phonological coding skills may be among the root causes of this problem (Paul et al., 2009; C. A. Perfetti & Sandak, 2000; Y. Wang et al., 2008). However, our study revealed patterns that suggest that phonological deficits are part of a deeper issue. To understand this, we will look at three important findings that were associated with higher⁷ fluency in our group of deaf readers.

First, we found a significant three-way interaction between predictability, reading fluency scores, and the contrast between correct and unrelated conditions in FFD. This pattern suggests that the activation of word meanings is more strongly facilitated by contextual information in higher fluency readers than in lower fluency readers. In their study on the effects of contextual predictability among adults of different ages and reading levels, Steen-Baker et al. (2017) noted that lower-fluency adult readers who have struggled with literacy attainment are more likely to have difficulty with message-level processing—that is, the processing of the syntactic, semantic, and pragmatic information contained in the sentence (Morris, 1994). As this is likely to be the case with the lower fluency deaf adult readers in our study, weaker message-level processing might have reduced the relative level of facilitation they could gain from context when initially accessing word meanings. Difficulties with message-level processing among lower-fluency deaf readers were reflected in the significant interaction we found between the correct v. unrelated contrasts and reading fluency in TRT, which indicated that lower fluency readers were spending significantly more time rereading targets even when they did not contain an

⁷“Higher fluency” as it pertains to our deaf readers should not necessarily be equated with highly skilled or highly advanced reading ability. The highest-scoring deaf reader in our study read at a rate of around 271 characters per minute, which was only slightly above the average score for the university-level hearing readers ($M = 259$, $SD = 91$) and was considerably lower than the highest score of 461 characters per minute.

erroneous character.

Second, we found a significant effect of reading fluency for the contrast between homophonic and unrelated errors in GD, suggesting that deaf readers with higher fluency were able to resolve homophonic errors more quickly than those with lower fluency. M. Yan et al. (2015) found a similar phonological effect in GD among deaf readers with high levels of reading fluency. They proposed that these deaf readers might be activating phonological representations based on the Hanyu Pinyin romanizations of Chinese characters. In our study, because our deaf readers did not formally learn any form of Cantonese or Mandarin romanization, it is more likely that they were activating phonological representations based on phonological information acquired through residual hearing or visual-tactile information acquired through lip-reading and speech training. While deaf readers with higher fluency had faster overall homophonic error recovery, they resolved both homophonic and homovisemic errors more slowly than the lower fluency readers when targets were in highly predictable contexts. This pattern suggests that less fluent deaf readers tend to activate phonological (possibly visemic) representations top-down via semantics rather than by bottom-up word identification processes (see discussion of top-down phonological activation processes in Thierfelder, Durantin, et al., 2020). This effect emerged in GD, which may indicate that phonological activation is facilitating lexical integration rather than early lexical access processes.

Third, we found a significant effect of reading fluency for the contrast between orthographic and unrelated conditions in TRT. This interaction suggests that the participants with higher reading fluency also had stronger orthographic error recovery abilities than those with lower reading fluency, which might reflect a stronger knowledge of characters' orthographic forms. Adult readers of Chinese have also been found to have stronger orthographic error recovery skills than children (Zhou et al., 2018), so lower fluency deaf readers appear to resemble developing readers in this way. In contrast to our study, Bélanger et al. (2013) did not find that less-skilled deaf readers of English had weaker orthographic processing skills than skilled deaf readers. It is possible that, because Chinese,

in contrast to English, requires visual processing attuned to complex configural information (C. Perfetti et al., 2013), well-developed orthographic coding skills are particularly important for Chinese reading.

3.5.3 Lexical quality

The lexical quality hypothesis (C. A. Perfetti & Hart, 2002) provides a plausible theoretical explanation of why deaf readers with higher reading fluency generally exhibited stronger orthographic and homophonic error recovery skills than those with lower reading fluency and why they were also able to make more efficient use of contextual information in early processing. The lexical quality hypothesis states that, as readers improve in skill, they develop high-quality representations of lexical items, which are comprised of orthographic, phonological, and semantic representations that are clearly defined and activated with relative synchronicity (C. A. Perfetti & Hart, 2002).

Based on this theory, we would predict that, upon reading a word with an orthographically or phonologically-related character error, a skilled reader would be able to quickly activate the correct target based on the shared properties of the erroneous and target characters and, in turn, quickly activate the semantic representation of the intended word. The fact that deaf readers with lower reading fluency levels tended to be less efficient in resolving homophonic errors in GD and orthographic errors in TRT suggests that phonological and orthographic representations are less clearly defined in their lexicons. Furthermore, the fact that lower fluency deaf readers' phonological activation processes, in comparison to those of the higher fluency deaf readers, were more facilitated by context in GD suggests that these readers are less able to reliably retrieve a word's phonological representation via orthographic representations alone.

Another prediction of the lexical quality hypothesis is that a lexicon consisting of mainly low-quality representations would lead to difficulties in integrating words into prior text (C. Perfetti, 2007). This prediction was supported by the finding that, in comparison to lower fluency deaf readers, those with higher reading fluency levels, when

reading correct words, were more facilitated by contextual predictability in FFD and spent less time rereading in TRT. We believe that the most important takeaway here is that weaker reading skills among deaf readers cannot be attributed solely to weak phonological coding skills but rather are due to a lack of high-quality lexical representations in the mental lexicon.

3.5.4 The dual-route cascaded model of reading by deaf adults

The dual-route cascaded model of reading by deaf adults (Elliott et al., 2012) proposes that deaf readers have access to two phonological lexicons. One contains phonological forms based on mouth shape, or “visemes,” while the other is sign-based. Based on our findings, and taking into account the nature of the Chinese writing system, we propose a slightly modified version of this verbal model to describe how deaf readers of Chinese process text.

Firstly, our findings do suggest that visemes play some (albeit limited) role in the reading processes of deaf readers of Chinese. However, in contrast to Elliott et al.’s (2012) proposed model, visemes do not appear to entirely replace more detailed phonological representations, which could include tactile information such as aspiration or sound-based phonological information acquired through residual hearing, but rather co-exists with it. Visemic effects were most apparent in TRT where it appeared that deaf readers were using visemic representations in late error recovery processes. However, this effect was somewhat weak and appeared to be an adaptive reading strategy for at least some of the deaf readers (evidenced by our post hoc observation that homovisemic error recovery speeds improved over the course of the experiment). In GD, deaf readers with lower reading fluency levels had shorter fixation times on both homophonic and homovisemic errors relative to those on unrelated errors in high predictability contexts, which seems to suggest that there might be a subset of readers who were activating visemic representations in early processing. Thus, which phonological lexicon is activated via the indirect route appears to depend on various factors, including the skill level of the reader, the

contextual information available in the sentence, and the stage of processing (i.e., early or late).

Figure 3.5 visualizes a version of the dual-route model as it may apply to deaf readers of Chinese and illustrates the following process: (1) the Chinese character is fixated, and its visual features are detected; (2) the character’s radical components are activated according to their visual features; (3) the orthographic lexicon activates representation(s) which contain those radicals in the same configuration; (4) the corresponding representation(s) from the spoken phonological, visemic, or sign language lexicon is activated; (5) the semantic system is activated, either directly from the orthographic representation or indirectly via a representation from one of the intermediary phonological lexicons. As mentioned, there seem to be a number of factors that influence the selection of a specific lexicon (i.e., spoken phonological, visemic, or sign language) via the indirect route. Further investigating what these factors are in future studies would help us gain a better understanding of deaf reading processes.

3.5.5 Limitations

Because some of our deaf participants were not proficient readers, we aimed to keep the duration of the experiment relatively short (around 40 minutes) to minimize participant reading fatigue. As such, we did not use filler sentences, and 80% percent of items included one of the four error types. It is likely that some participants became familiar with the error types over the course of the experiment and thus were able to decipher the errors more quickly. This might have led to stronger phonological and orthographic effects among the readers in our study compared to what might have been found had the error patterns been less easily identifiable. Furthermore, due to practical limitations at the time of the study, we did not recruit a well-matched hearing comparison group, which would have allowed us to directly compare the two groups and conduct a more in-depth investigation of the differences between deaf and hearing readers. Further error disruption studies focused on deaf readers could help us assess the generalizability of the

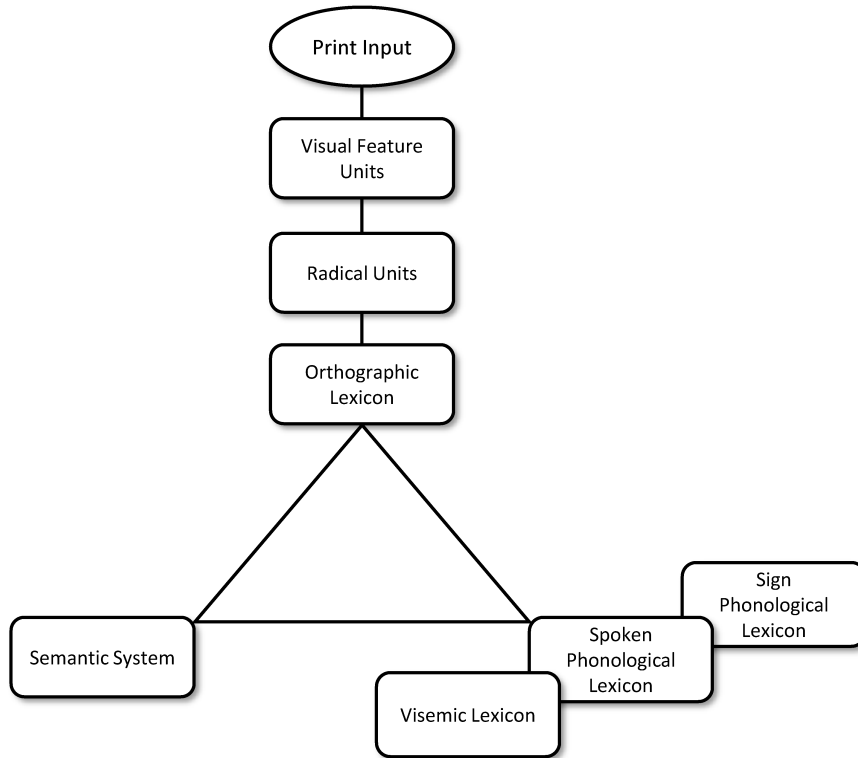


Figure 3.5: *Modified dual-route model of reading for deaf readers of Chinese.*

results of the current study and would be of great value in building a more robust picture of deaf reading processes.

3.5.6 Conclusion

Our study aimed to investigate the patterns of phonological and orthographic activation among deaf readers. Our findings suggested that deaf readers, while activating word meanings primarily through orthographic representations, do activate phonological representations in certain circumstances, such as in predictable contexts or during late processing. In line with the dual-route cascaded model of reading by deaf adults (Elliott et al., 2012), our data support that deaf readers may activate visemic representations, particularly as an error recovery strategy when rereading text. Additionally, there was an indication that deaf readers with lower reading fluency levels might be activating visemic code in early processing in high predictability contexts. Finally, taken together, our find-

ings suggest that lower reading fluency levels in deaf readers are not specifically a result of weaker phonological skills. Instead, lower reading fluency appears to be a consequence of possessing a lexicon consisting of lower quality lexical representations with less distinct orthographic, phonological, and semantic components.

For educators working with developing deaf readers, viewing reading difficulties as mainly a result of weaker spoken phonological coding skills might lead to an under-emphasis of the development of strong orthographic and context-based reading skills. As deaf students vary in their ability to access sound-based phonology, providing students with accessible phonological codes during reading instruction, such as viseme and sign-based codes, would likely be beneficial. Finally, as deaf readers with lower reading fluency appear to possess lower-quality lexical representations, increased exposure to and engagement with a wide variety of words and contexts is, as most educators are already aware, of utmost importance. Future research could further examine the roles of the different phonological codes used by deaf readers or look at whether specific teaching interventions, such as instruction aimed at improving readers' orthographic skills, can lead to more efficient error recovery among deaf readers in the error disruption paradigm.

3.6 Acknowledgements

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3.7 Supplementary material

Data and R scripts associated with this article can be found at <https://doi.org/10.5281/zenodo.3834949>.

Chapter 4

Sign phonological parameters modulate parafoveal preview effects in deaf readers (accepted version)

Abstract

Research has found that deaf readers unconsciously activate sign translations of written words while reading. However, the ways in which different sign phonological parameters associated with these sign translations tie into reading processes have received little attention in the literature. In this study on Chinese reading, we used a parafoveal preview paradigm to investigate how four different types of sign phonologically related preview affect reading processes in adult deaf signers of Hong Kong Sign Language (HKSL). The four types of sign phonologically related preview-target pair were: (1) pairs with HKSL translations that overlapped in three parameters—handshape, location, and movement; (2) pairs that overlapped in only handshape and location; (3) pairs that only overlapped in handshape and movement; and (4) pairs that only overlapped in location and movement. Results showed that the handshape parameter was of particular importance as only sign translation pairs that had handshape among their overlapping sign phonological parameters led to early sign activation. Furthermore, we found that, compared to control previews,

deaf readers took longer to read targets when the sign translation previews overlapped with targets in either handshape and movement or handshape, movement, and location. In contrast, fixation times on targets were shorter when previews and targets overlapped location and any single additional parameter—either handshape or movement. These results indicate that the phonological parameters of handshape, location, and movement are activated via orthography during Chinese reading and can have different effects on parafoveal processing in deaf signers of HKSL.

4.1 Introduction

Deaf readers of different linguistic backgrounds have often been found to struggle with literacy (e.g., USA: Mayberry et al., 2011; context of the present study, Hong Kong: Thierfelder & Stapleton, 2016). However, the causes of these low literacy levels are still debated. Some researchers have suggested that the absence of spoken phonological coding skills can lead to difficulties in reading development (Paul et al., 2009; C. A. Perfetti & Sandak, 2000; Y. Wang et al., 2008), while others have argued that spoken phonological code is of less central importance (Allen et al., 2009; Bélanger et al., 2013; Mayberry et al., 2011). Although much discussion has surrounded issues related to literacy attainment and the role of spoken phonological code, research findings have built a complex and interesting picture of deaf reading and its distinguishing characteristics. For example, in contrast with hearing readers, deaf readers of logographic (e.g., Chinese) and alphabetic scripts (e.g., English) have been found to have a wider perceptual span, taking in more words per fixation, and more efficient orthographic processing abilities (Bélanger et al., 2018; Bélanger, Slattery, et al., 2012; M. Yan et al., 2015). While deaf readers have been found to largely bypass phonology to access word meanings directly through orthography (Bélanger et al., 2013), phonological representations based on mouth shapes, phonotactile, or acoustic information play a role in lexical access for at least some deaf readers of different written languages including English (Hanson & Lichtenstein, 1990), Chinese

(Y. Li et al., 2014; M. Yan et al., 2015), and German (Elliott et al., 2012).

Research on unimodal bilinguals (people fluent in two spoken languages) has found that when reading words in one language, bilingual readers unconsciously activate translations in the second language (Y. J. Wu & Thierry, 2010, 2012). This finding has been extended to deaf bimodal bilinguals, who are fluent in a signed language and a written form of a spoken language, by research showing that sign phonological representations are activated by deaf signers during reading. For example, Morford et al. (2011) used a semantic relatedness paradigm in which participants were presented prime-target word pairs and asked to judge whether or not the pairs were semantically related. When the American Sign Language (ASL) translations were similar in their sign phonology, semantically related sign translation word pairs were judged more quickly while opposite, inhibitory effects on response time were seen when pairs were semantically unrelated. Meade et al. (2017) carried out a similar study while taking electrophysiological recordings with EEG technology. The EEG data showed reduced negative amplitudes in the N400¹ window for targets in sign phonologically related translation pairs, and the reaction time data showed increased reaction times for the same pairs. The authors concluded that the N400 effect reflected the initial activation of the sign translation while the slower reaction times were due to sign phonological interference in the semantic decision task.

Morford et al. (2019) investigated whether specific sub-lexical relationships in sign translation prime-target word pairs might strengthen sign phonological activation effects or be required for sign phonological activation to occur. Their stimuli included three groups of English word pairs with sign phonologically related American Sign Language translations: pairs in which both signs shared a syllable (i.e., the same movement), pairs in which both signs were initialized (e.g., BOOT, signed with B-handshapes, and SHOE signed with S-handshapes), and signs that overlapped in handshape and location (i.e., phonologically related but not sharing a syllable). Their findings revealed that

¹The N400 is negative-going potential that peaks around 400 ms after stimulus onset. In priming studies, its amplitude is affected by various properties of the prime such as orthographic, phonological and semantic relatedness.

neither initialization nor shared syllabic structure contributed to sign activation. Instead, activation effects were strongest when pairs shared a common handshape and location.

Although most research on sign phonological activation during reading has focused on deaf readers of alphabetic scripts, deaf readers of Chinese, a logographic script, have also been shown to activate sign phonological representations during reading in both individual word and sentence reading tasks (Chiu et al., 2016; Chiu & Wu, 2016; Pan et al., 2015). The fact that sign phonological activation appears to be common even across groups of deaf readers with vastly different native orthographies (e.g., English and Chinese) suggests that this phenomenon might be a universal characteristic of bimodal bilingual reading processes. However, there is still much to be uncovered concerning the nature of these processes. For example, there has been little research investigating which networks in the brain are involved in the activation of sign phonology via written orthography. In one of the few studies addressing this question, Quandt and Kubicek (2018) proposed that sign activation during reading in bimodal bilinguals might involve action simulation in the brain’s sensorimotor system. To test this, they had deaf signers read English words while their EEGs were recorded. Each word belonged to one of two groups: words which translated into one-handed ASL signs and words which translated into two-handed ASL signs. Results showed significant differences in sensorimotor EEG rhythms when deaf participants read words from each of the word groups, while no such differences were found in the hearing control group, suggesting that sign language activation during reading engages the sensorimotor system in action simulation processes.

Currently, research on the role of sign phonology in bimodal bilingual readers is still limited. To the authors’ knowledge, no studies have looked at how specific sign phonological parameters, such as handshape, movement and location, affect cognitive processing during reading. In the present study, we investigate this topic with a cohort of deaf adults from Hong Kong using a parafoveal preview paradigm.

4.1.1 Parafoveal preview studies of deaf readers

While reading, we do not only process the word on which we are currently fixating but also one to two words beyond which are captured within the parafoveal range of vision (see Vasilev & Angele, 2017, for an overview of relevant research). Once processed parafoveally, the reader can then spend less time fixating on that word or skip it altogether. In eye-tracking research on parafoveal processing effects, this is referred to as *preview benefit*, which is the facilitation of processing speed gained from previewing the upcoming word in the parafovea. Conversely, if an upcoming word is blocked or obscured (in experiments, for example, a string of X's might be used to mask the target temporarily) immediately before it is fixated upon, the subsequent time spent fixating on that word is likely to be longer—*preview cost*, as opposed to *preview benefit*. Capitalizing on this phenomenon, researchers devised the parafoveal preview paradigm or gaze-contingent boundary paradigm (Rayner, 1975) to investigate how manipulating information accessed via parafoveal vision affects readers' cognitive processing. In this paradigm, participants are presented with sentences containing a target word that is manipulated during the experiment and an invisible boundary between the target and pre-target words. Before the target is fixated, its position is occupied by a preview word, which is either identical to the target, related to the target (e.g., in terms of orthography, phonology, or meaning), or unrelated to the target. When the eye-tracking system detects that the eyes are crossing the invisible boundary, the preview word is instantaneously replaced by the correct target word. As this change occurs while the eyes are in motion, during an instant of saccadic blindness (i.e., a moment of blindness caused by movement of the eye), readers are often unaware that this display change has taken place. Some common eye-fixation measures used in the analysis of parafoveal preview paradigm data include first fixation duration (FFD), gaze duration (GD), and total reading time (TRT), which are measured in milliseconds. The measures of FFD, which is the length of time of the first fixation on the target word, and GD, which is FFD plus any additional fixations before reader fixates on the next word, are both measures of early or first-pass lexical processing (Rayner,

2009; Rayner et al., 1998). These two measures are generally considered similar in that they both reflect the earliest stages of processing though some researchers have argued that GD better captures semantic integration processes than does FFD (Carpenter & Daneman, 1981; Inhoff, 1984). TRT is another common measure and includes the sum of GD plus any additional fixations that occur during re-reading. TRT is a measure of late stages of processing and reflects the time involved in the retrieval and integration of lexical items (Conklin et al., 2018) as well as error recovery processes (Daneman & Reingold, 1993).

The parafoveal preview paradigm has been used to investigate reading processes in deaf readers of Chinese and English. For example, to investigate parafoveal processing effects of orthographic, phonological, and semantic information among deaf readers of Chinese, M. Yan et al. (2015) included five preview conditions in an experiment with deaf and hearing readers from Beijing: identical (e.g., 成 /cheng2/ ² [complete] in 成家 /cheng2 jia1/ [to get married]), orthographic (a non-homophonic character with a similar orthographic structure to the correct target, e.g., 戍 /shu4/ [garrison]), phonological (an orthographically dissimilar character with the same pronunciation as the target, e.g., 承 /cheng2/ [have]), semantic (a character that is similar in meaning to the target but otherwise dissimilar, e.g., 立 /li4/ [found]), and unrelated (dissimilar in pronunciation, orthography, and meaning, e.g., 乡 /xiang1/ [village]). Statistical analyses compared the unrelated condition to the identical and related conditions. Importantly, they found an early preview benefit for semantically related characters for deaf readers in FFD. Although FFDs were shorter on semantically related previews, an opposite effect was observed in later measures. That is, preview benefit became preview cost in go-past time (the cumulative time from the first fixation on the target until first fixation the following word) and TRT. For hearing readers, semantic preview effects were not found in FFD though preview cost was also found in go-past time and TRT. This finding, according to the authors, suggested that deaf readers can process parafoveal information more quickly

²Romanizations for this study shown in Hanyu Pinyin, the standard romanisation system used in Mainland China. Tones are indicated numerically.

than hearing readers. Preview cost, which was found in this study to be associated with semantic previews in late fixation measures, has been associated with deeper lexical access, which increases with fixation durations and leads to competition between the forms activated by the preview and targets (Pan et al., 2016). While semantic previews were associated with preview cost, M. Yan et al. (2015) found evidence of preview benefit in GD among the more skilled deaf readers when previews were phonologically related (i.e., homophonic) in Mandarin. In contrast, Bélanger et al.'s (2013) study on skilled hearing as well as skilled and less-skilled deaf readers of English found preview benefit of homophonic previews among hearing participants but no such phonological effects among skilled and less-skilled deaf readers.

In light of M. Yan et al.'s (2015) finding that deaf readers have highly efficient parafoveal processing abilities, and the research showing that deaf readers activate sign phonological representations during reading (e.g., Meade et al., 2017, Morford et al., 2011), Pan et al. (2015) extended the parafoveal preview paradigm to look at sign phonological activation during sentence reading among signing deaf adults from Beijing. Their study used sign phonologically related, but semantically unrelated, word pairs with Chinese Sign Language (CSL) translations that were identical in at least two out of four sign phonological features (handshape, orientation, movement, and location). Of these, 17 out of 23 pairs had identical handshapes; 22 pairs were identical in terms of orientation; 16 identical in movement; and all 23 were identical in location. They found that sign translation previews induced early preview cost in FFD. Given that phonological relatedness for hearing readers is often associated with preview benefit rather than preview cost, Pan et al. (2015) noted that their study was the first to find preview cost associated with an attribute other than semantic relatedness. The authors proposed that signing deaf readers' enhanced parafoveal processing abilities, which allows them deeper access to parafoveal information, might lead to preview cost in deaf readers.

Chiu and Wu (2016) conducted a parafoveal preview study with deaf readers from Taiwan following a methodology similar to that of Pan et al. (2015). Their study used sign

translation pairs that overlapped in the handshape parameter (at least some pairs differed in location and movement, but the authors did not provide further details regarding the degree of overlap of these parameters across their word pairs). They found a preview benefit associated with single-character word (as opposed to two-character words) sign translation previews in FFD. Deaf participants also had higher fixation counts on targets with sign translation previews than those with unrelated previews. For two-character sign translation previews, this preview benefit was found in both FFD and GD. The authors suggested two possible factors that might have contributed to their finding of preview benefit (in contrast to the preview cost found in Pan et al., 2015). One suggestion was that the configuration of overlapping sign phonological parameters in sign translation preview-target pairs might influence whether preview benefit or preview cost is observed. The second was that results might be affected by the data filtering techniques used—in contrast to Pan et al. (2015), to exclude trials during which parafoveal processing of the preview word might not have taken place, Chiu and Wu (2016) discarded trials in which the pre-target character was skipped. While it seems unlikely that data processing methods would have led to the different results of these two studies (we cannot find any literature indicating that preview cost/benefit has been previously attributed to this), the authors’ suggestion that the overlapping phonological parameters of the sign translation preview-target pairs might be an important factor has merit when we consider psycholinguistic research on sign language perception.

4.1.2 Sign language phonology and lexical access

Like words in spoken language, signs also have a phonological structure. Stokoe et al. (1965) identified three main phonological parameters of a sign: handshape, location, and movement. Some researchers have suggested the inclusion of facial expression (non-manual features) and hand orientation among these (Liddell & Johnson, 1989). However, studies on sign perception have generally focused on the three first proposed by Stokoe et al. (1965). Thus far, studies have pointed to each of these sign phonological parameters

contributing differently to sign recognition. For example, Emmorey and Corina (1990) presented recordings with signs segmented into 33 ms parts and found that location was identified first, followed quickly by handshape and last by movement. In a study with signers of British Sign Language (BSL) that looked at how the phonological parameters of handshape, location, and movement affect sign recognition among deaf signers, Orfanidou et al. (2009) had participants watch recordings of real BSL signs and constructed non-signs. After each recording, participants had to indicate whether the sign they just saw was a true sign in BSL or a non-sign and then produce the sign from memory. They found an inhibitory priming effect of location (i.e., participants took longer to respond when prime-target pairs shared a location) and that participants modified handshape and movement parameters more often than the location parameter. They concluded that location is the least ambiguous parameter and that the three parameters play different roles in sign recognition. In a study on signers of Spanish Sign Language, Carreiras et al. (2008) found that when sign primes contained a handshape that was part of a high-density neighborhood (i.e., a group of signs in which a large number of signs share the same handshape), neighborhood density facilitated lexical access for less familiar target signs. In contrast, when signs contained a location that was part of a high-density neighborhood, the outcome for less familiar targets was inhibition rather than facilitation. They also found that handshape overlap in non-signs was facilitatory while location overlap for signs, rather than non-signs, was inhibitory. They suggested the facilitatory influence of handshape might indicate that this parameter is involved in prelexical processes. In another study on signers of Spanish Sign Language, Gutiérrez et al. (2012) conducted an electrophysiological study using a primed lexical decision task. Sign phonological overlap was manipulated such that the prime shared either handshape or location with the target. Priming of location using real signs resulted in a higher amplitude of the N400 component (300–500 ms) while handshape priming affected a later window between 600–800 ms, but only for non-sign primes.

While these studies discussed above point to a unique status of location in sign lan-

guage perception, studies have not been unanimous in their findings. D. P. Corina and Hildebrandt (2002) did a primed lexical decision task for ASL and found no significant effects of either handshape or location (though they did find a non-significant inhibitory priming trend for location). A study by Villameriel et al. (2019) investigated sub-lexical processing of signs among hearing bimodal bilinguals fluent in both Spanish Sign Language and Spanish. For hearing participants who acquired Spanish Sign Language early in life, competition from location was earlier than handshape, though the effect of handshape was stronger overall. Among those who learned to sign later in life, location effects were late and the effects of handshape were weaker. In another study investigating how the parameters of handshape, movement, and location are used in lexical access, Dye and Shih (2006) conducted a primed lexical decision study in which native and non-native deaf signers of BSL were shown recordings of two signs (one or both of which might have been an invented non-sign), a target preceded by a sign phonologically related prime. They then had to decide whether the target was a real sign in BSL. While decision accuracy was equal for both native and non-native signers, when BSL primes shared both location and movement with the target, a facilitative priming effect only among the native signers was observed. This effect was not observed when primes were non-signs. They also found a marginally significant priming effect for identical sign/sign and non-sign/non-sign pairs. For non-native signers, a priming effect of shared movement was observed for sign/sign and sign/non-sign pairs. The authors suggested that priming effects for native signers were at the lexical level while those for non-native signers were pre-lexical.

Interestingly, a separate study found that deaf signers of ASL were more likely to perceive sign pairs sharing a common location and movement as being phonologically similar compared to those that overlapped in handshape and movement or handshape and location (Hildebrandt & Corina, 2002). Thus, it is possible that the facilitatory priming of location and movement found in Dye and Shih (2006) might be attributable to their relatively high perceptual similarity, also evidenced by the marginally significant priming effect for identical sign pairs. The possibility that the observation of inhibitory

or facilitatory priming might relate to the degree of sign phonological overlap in prime-target pairs was investigated by D. P. Corina and Knapp (2006), who found that sign phonological similarity, when limited to overlap in one or two features, facilitated lexical retrieval, while very high sign phonological similarity inhibited lexical retrieval, possibly by creating higher levels of competition between neighbors. Similar effects have been found in research on spoken language—that is, too much phonological similarity can create inhibition between phonologically related words during lexical access (Goldinger et al., 1989; Vitevitch & Luce, 1999). The mixed findings of priming studies suggest that various factors, including which specific phonological parameters overlap, the number of overlapping parameters and the design of the priming task itself all might influence whether priming effects are observed and whether those priming effects are inhibitory or facilitatory. A common thread we see through most studies, however, is that the location parameter seems to be of particular importance in the phonological processing of a sign. This might be related to its visual salience, which is evidenced by the fact that location is more accurately produced by children naturally acquiring sign language than handshape or movement (Siedlecki & Bonvillian, 1993) and as mentioned, by the fact that it can be more quickly identified than other parameters (Emmorey & Corina, 1990).

It is important to emphasize that these studies focused on sign perception and had participants view recordings of signs, and thus, it is not clear whether inhibitory or facilitative priming effects of sign phonological parameters in these studies will show analogous patterns when signs are being activated via orthography during reading rather than being viewed in real-time. Given that sign perception and sign activation via orthography appear to involve activity in different brain regions (see Emmorey et al., 2010, Quandt & Kubicek, 2018), it is possible that considerably different patterns will be observed. However, returning to the discussion on parafoveal activation of sign phonological translation previews, we suspect there might be some parallels between the inhibitory and facilitative priming effects found in studies of sign perception and the preview cost and preview benefit effects found in parafoveal preview studies. Pan et al. (2015), who found preview

cost, used sign translation pairs that overlapped on most parameters, but location was the only parameter that overlapped across all pairs. In contrast, Chiu and Wu (2016), who found preview benefit effects, used pairs that were identical in handshape but differed in other parameters (while the authors did not provide a detailed list of stimuli, examples provided indicate that at least some of the stimuli differed in either location or movement). Based on the research we have reviewed, we propose two possible causes of the diverging findings of preview benefit in Chiu and Wu (2016) and preview cost in Pan et al. (2015). The first possibility is that sign translation pairs with overlapping locations are more likely to lead to preview cost due to increased competition between the phonological representations activated by the preview and target, while those differing in location are more likely to lead to benefit as they create less competition. The second possibility is that overall phonological relatedness in sign translation pairs determines whether preview cost or benefit is observed such that sign translation pairs overlapping in all three parameters are more likely to induce preview cost, while those overlapping in only two parameters are more likely to lead to preview benefit.

4.2 The Present Study

In this study, we use a parafoveal preview paradigm to look at whether the specific overlapping parameters in sign phonologically related translation preview-target pairs modulate the preview effects observed in deaf readers. To untangle the relationship between phonological relatedness and preview effects, we use four groups of sign phonologically related translation pairs: pairs that overlap in handshape, location, and movement (HLM pairs), pairs that overlap in handshape and location but differ in movement (HL pairs), pairs that overlap in handshape and movement but differ in location (HM pairs), and pairs that overlap in location and movement but differ in handshape (LM pairs). Based on the previously discussed priming studies on sign perception, we suspect two possible patterns of results. The first is that we will find preview cost associated with HLM, HL,

and LM pairs, due to their phonological overlap on the location parameter, as this is the main phonological parameter associated with inhibitory priming in sign perception studies (Carreiras et al., 2008; Orfanidou et al., 2009), but observe preview benefit with HM pairs. If this is the case, we would also expect that the overall effect of sign translation previews (collapsed across the HLM, HL, HM, and LM sub-conditions), as most overlap in this parameter, would be preview cost and thus reflect the findings of Pan et al. (2015). The second possibility, based on the findings of D. P. Corina and Knapp (2006) as well as Dye and Shih (2006), is that we will observe preview cost associated with the HLM pairs due to their high degree of phonological overlap, and preview benefit associated with HL, HM, and LM pairs which are less similar. In this case, the combined effect of all sign phonological previews is more likely to show an overall pattern of preview benefit, similar to results reported in Chiu and Wu (2016). This study is divided into two parts: Study 1 (hearing readers) and Study 2 (deaf readers). In Study 1, we test our stimuli with an independent sample of non-signing hearing readers, with the expectation that there will be no statistically significant preview effects associated with the sign phonologically related previews. Such interactions, if found, might suggest that semantic, orthographic, or phonological relatedness of previews were not adequately controlled for across conditions. Assuming Study 1 yields no significant preview effects of sign phonologically related previews, we can more confidently attribute any such effects found in Study 2 to the activation of HKSL representations.

4.3 Method

4.3.1 Participants

For Study 1, a group of hearing readers ($n = 30$) was recruited from a local university. These participants had a mean age of 19 ($SD = 2$), and all were native speakers of Cantonese. None had any previous exposure to HKSL. A Chinese reading fluency test based on those described in Moll et al. (2009) and Pan et al. (2011) indicated that

the hearing readers read at an average rate of 259 characters per minute. The deaf participants ($n = 31$) recruited for Study 2 ranged from 28 to 48 with an average age of 37 years of age ($SD = 6$). All had hearing loss between 80 and 120 dB ($M = 102$, $SD = 11$) and were signers of Hong Kong Sign Language (HKSL), a natural sign language which is distinct from written Chinese and spoken Cantonese in its syntactic structure and lexicon (Tang, 2007). Nine were native signers with either deaf parents or a deaf older sibling, while 22 reported that they had begun learning HKSL between the ages of seven and thirteen. All reported having attended an oral deaf school starting at a young age and all had graduated from high school. All deaf participants reported that they used HKSL every day for communication. Reading fluency tests indicated that deaf participants read at an average rate of about 146 characters per minute, a rate significantly slower than that of hearing participants ($p < .001$). All participants had normal or corrected-to-normal vision. Ethical clearance was obtained from both universities associated with the study, and written consent was given by participants before participation. All information, including consent forms, was provided to deaf participants in both written Chinese and HKSL.

4.3.2 Materials

Working with a deaf research assistant, we selected 40 pairs of two-character Chinese words which had phonologically similar HKSL translations. Following Morford et al. (2011) and Pan et al. (2015), each pair overlapped in at least two sign phonological parameters but were unrelated in terms of orthographic appearance, pronunciation, and meaning. Ten of these pairs had sign translations that overlapped in all three main phonological parameters: handshape, location, and movement (see example in Figure 4.1a). Ten pairs differed in movement but overlapped in handshape and location (Figure 4.1b); ten pairs differed in location but overlapped in handshape and movement (Figure 4.1c); and a final ten pairs differed in handshape but overlapped in location and movement (Figure 4.1d). Each word among the sign phonologically related translation pairs was used

in the experiment once as an identical preview and once as a sign phonological preview. Each word was further paired with a two-character word that was dissimilar in terms of meaning, HKSL phonology, Cantonese phonology, and orthographic form to serve as the unrelated preview condition. The final word list comprised 80 sets of words, each with an identical preview word, a sign translation preview word (twenty belonging to each the HLM, HL, HM and LM sub-conditions), and an unrelated preview word. There were no significant differences across the identical, unrelated, and sign phonologically related preview words for stroke count [$F(5, 225) = 0.48, p > .1$] or character frequency³ [$F(5, 225) = 0.182, p > .1$]. To check that there was no semantic relationship between previews and targets, we carried out an independent norming study with 20 hearing undergraduate students from Hong Kong in which they were asked to rate the semantic relatedness of each preview-target pair on a scale of one (completely dissimilar in meaning) to five (strongly related in meaning). As intended, there were no significant effects of semantic relatedness across conditions [$F(4, 80) = 1.98, p > .1$]. Properties of preview and target words are summarized in Table 4.1.

	Identical Preview	Overall Sign Preview	HLM Sign Preview	HL Sign Preview	HM Sign Preview	LM Sign Preview	Unrelated Preview
Frequency	169 (127)	169 (127)	151 (120)	178 (107)	179 (99)	163 (139)	168 (106)
Semantic Rating	–	1.7 (1.7)	1.7 (1.3)	1.7 (1.3)	1.6 (1.4)	1.6 (1.3)	1.7 (1.3)
Sign Phonological Rating	–	2.4 (2.1)	3.7 (1.6)	2.2 (1.5)	2.2 (1.5)	1.8 (1.4)	1.1 (0.4)
Total Stroke Count	20 (8)	20 (8)	19 (6)	21 (9)	21 (6)	19 (9)	20 (7)

Table 4.1: *Word properties*. Table shows the mean frequency, semantic relatedness rating, sign phonological relatedness rating, and stroke count for each condition with standard deviations in parentheses. Mean word properties of the sign phonologically related previews are divided by sub-condition in the HLM/HL/HM/LM Sign Preview columns and collapsed together in the Overall Sign Preview column. H = handshape. L = location. M = movement.

A sentence frame was created for each of the 80 sets of words. Sentences were 13 to 19 characters in length ($M = 17, SD = 1$). Target words were always preceded by a two-character pre-target word or collocation. The invisible boundary was set directly

³As we did not have access to a comprehensive corpus of Cantonese or Hong Kong written Chinese, we used mean character frequencies of each two-character word from H. H. Ho et al.’s (2001) Hong Kong character frequency list.

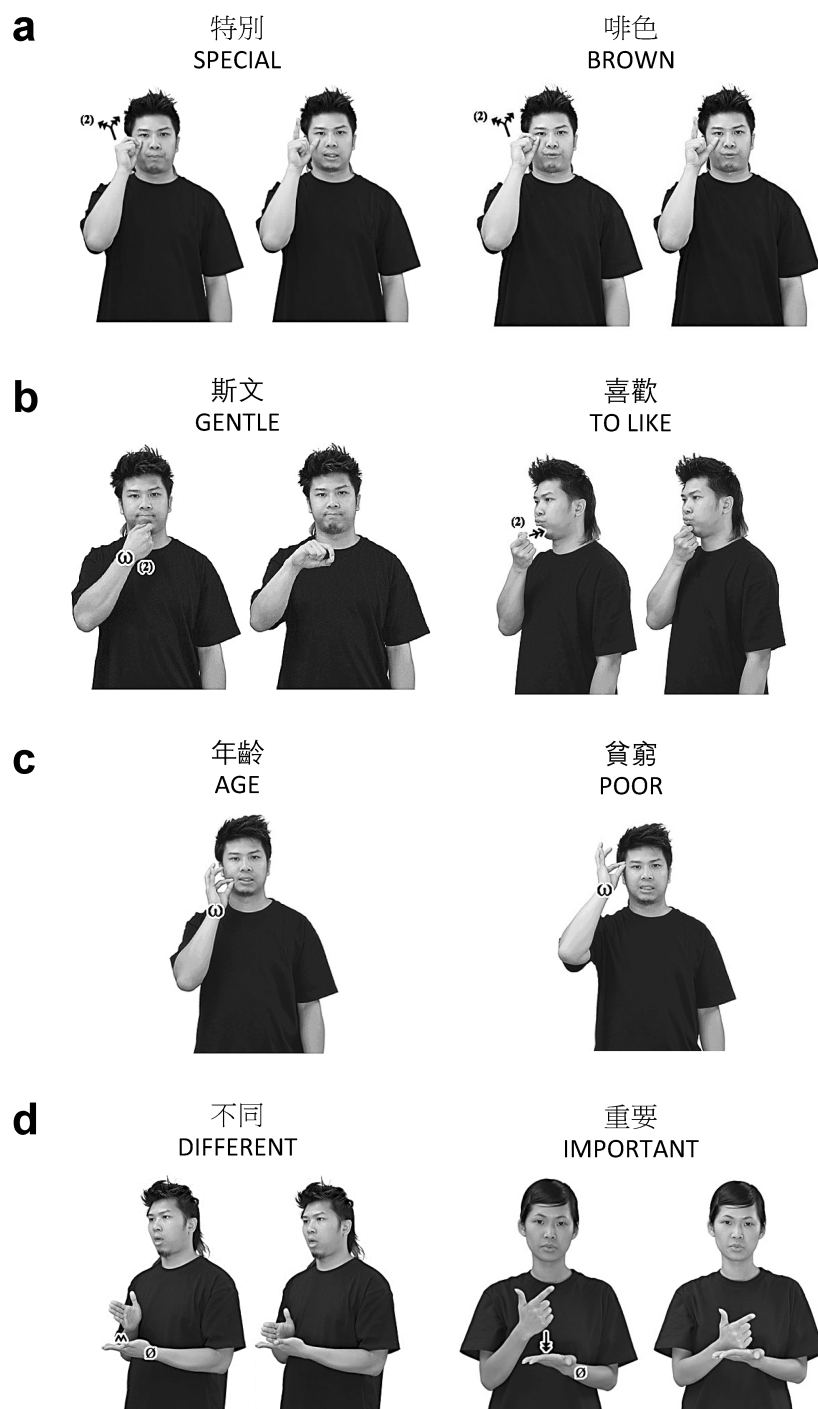


Figure 4.1: *Sign phonologically related translation pair types*. 1a shows an example of an HLM (handshape/location/movement) preview-target pair. 1b shows a HL (handshape/location) preview-target pair. 1c shows a HM (handshape/movement) preview-target pair. 1d shows a LM (location/movement) preview-target pair. Images used with permission courtesy of the Asian SignBank (<http://cslds.org/asiansignbank/>).

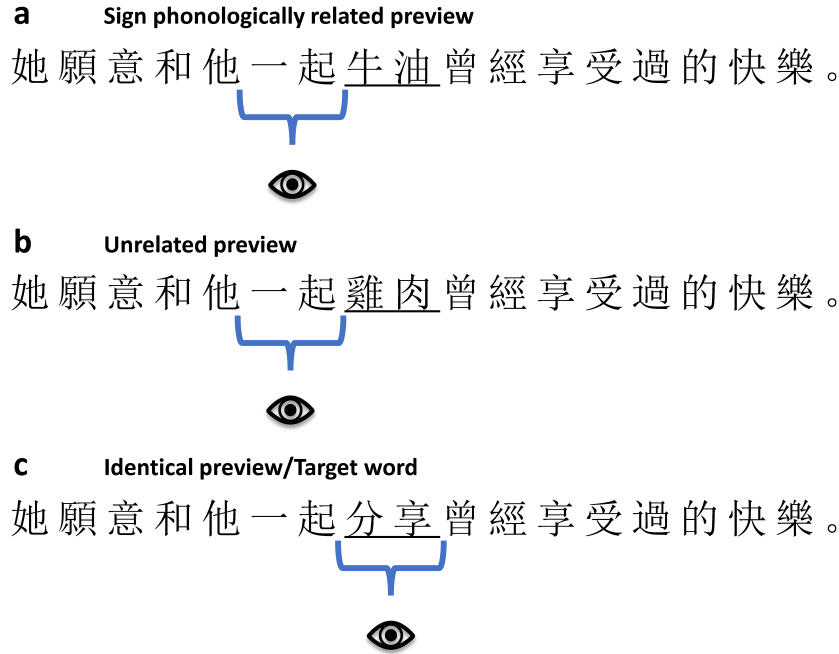


Figure 4.2: *Example sentence in three conditions.* A set of example sentences with underlined preview words. Figure 4.2a and 4.2b show sign phonologically related translation and unrelated previews as they would appear when the pre-target word is within the foveal range of vision. Figure 4.2c shows the target word as it would appear after the display change (or both before and after the display change in the identical preview condition). Target sentence translation: “She wishes to share with him the joys she once had.”

between the target and pre-target regions (Figure 4.2). Targets were never among the first five or last four characters in the sentence.

To reduce the likelihood that readers might skip the target word, we designed sentences to be contextually neutral with regards to the target word. To ensure this was the case, we conducted a norming study with an independent group of 20 hearing readers in which they were shown each sentence frame up to but not including the target and asked to guess what the next word was most likely to be. Identical targets were only guessed correctly 43 out of 1600 times (3% correct guesses) across all sentences. None of the words from the sign phonologically related condition or the unrelated condition were guessed for their respective sentence frames (0% correct guesses). Preview words in their respective sentences were always contextually inappropriate and constituted a grammatical (e.g., a noun where only an adjective would be appropriate: 一個媽媽 場

所 [a mother place] instead of 一個秘密 場所 [a secret place]) or semantic error (e.g., a contextually inappropriate noun replacing a contextually appropriate noun: 待在人物 [stay at person] instead of 待在屋企 [stay at the house/home]).

While we could not use a within-items design such that the sentence frames would be identical across the HLM, HL, HM, and LM sub-conditions of the sign phonologically related condition due to the very limited number of minimal pairs in HKSL that differ by only one phonological parameter, sentence contexts were designed to be as uniform as possible across these four types of sign phonologically related preview. There was no significant effect of sign translation preview type on sentence length [$F(3, 76) = 1.37, p > .1$], sentential position of the preview word [$F(3, 76) = 1.51, p > .1$], or contextual predictability of targets [$F(3, 76) = 0.21, p > .1$]. As overall sentence difficulty might influence fixation times, to check that sentences were uniform in difficulty across conditions, we used the Chinese Readability Index Explorer/CRIE (Sung et al., 2016) to extract the number of “difficult words” (defined as words not on the CRIE’s list of commonly used Chinese words), average frequency of content words, and average stroke count (per character) for each sentence. An analysis of variance showed that there was no effect of sign translation preview type on any of these measures [number of difficult words: $F(3, 76) = 0.96, p > .1$; average content word frequency: $F(3, 76) = 0.44, p > .1$; average stroke count per character: $F(3, 76) = 0.90, p > .1$]. Given that sentence frames in the HLM, HL, HM, and LM conditions do not differ significantly according to any of the measurements mentioned above, it is unlikely that any differences in preview effects could be attributed to sentence-level properties.

The final set of stimuli consisted of three item lists with the identical, sign phonologically related, and unrelated preview conditions comprising one-third of each list. During the experiment, no participant was exposed to the same sentence frame more than once, and the three main preview conditions, as well as the HLM, HL, HM, and LM sub-conditions of the sign phonologically related condition, were counterbalanced across participants.

As one of our predictions is that higher sign phonological similarity could be a contributing factor to preview cost, a sign phonological relatedness study was carried out with the same group of deaf participants (three months after participation in the experiment to reduce risk of biased responses). Participants were presented with each Chinese word pair used in the study and asked to rate how similar they felt the corresponding HKSL translations were in terms of sign phonology according to how they, themselves, would produce the signs on a scale of one (completely dissimilar in HKSL phonology) to five (highly similar in HKSL phonology). As this kind of task was unfamiliar to most participants, the questionnaire was administered by a native-signing deaf linguist from Hong Kong. As intended by the experimental design, an analysis of variance showed a significant interaction between condition and sign phonological relatedness [$F(4, 120) = 117, p < .001$]. Average similarity ratings of unrelated sign pairs ($M = 1.11, SD = 0.43$) were significantly less similar than HLM ($M = 3.65, SD = 0.05$), LM ($M = 1.83, SD = 1.38$), HL ($M = 2.19, SD = 1.45$), and HM ($M = 2.21, SD = 1.46$) sign pairs ($ps < .001$). HLM sign pairs were rated as the most similar compared to HL, HM, or LM pairs ($ps < .001$). HM and HL sign translation pairs did not differ significantly in their sign phonological similarity rating ($p > .1$). Finally, LM sign translation pairs were rated as significantly less similar than both HL and HM pairs ($ps < .01$).

From these results we can see that the number and combination of overlapping sign phonological parameters in sign translation pairs affect how phonologically similar they are perceived to be. First, HLM sign translation pairs, which overlapped in all parameters, were perceived to be the most similar. HM and HL pairs, which both overlap in handshape, were both perceived as having a similar degree of sign phonological similarity—though less than HLM pairs. LM pairs were considered the least similar but still were rated as significantly more similar than pairs that did not overlap on any feature, suggesting that handshape differences reduce perceived sign phonological similarity to a greater extent than differences in location or movement. Native ($n = 9$) and non-native signers within our sample showed the same pattern of results overall, but native signers tended

to give higher similarity ratings to HLM pairs than non-native signers ($p < .01$).

As there is a high amount of lexical variation in HKSL, we performed a check immediately after each experimental session to see if the majority of signers produced the target signs in according to the expected sign phonological configurations. In this check, each signer was asked to show how they would translate each target word, shown in Chinese characters, into HKSL. Three pairs were recategorized because the majority of participants produced them with a different configuration of parameters than had been expected. One pair was reclassified from HL to HLM, one from HLM to HL, and one from HLM to LM. After recategorization, as each member of a given pair was used once as a sign translation preview and once as a correct target, there were a total of 18 different HLM previews, 20 HL previews, 20 HM previews, and 22 LM previews in the sign phonologically related condition. This check also confirmed that all participants could easily recognize all target and preview words used in the experiment.

4.3.3 Apparatus

Eye-movements were recorded using an Eyelink 1000 Plus desktop system running at 2000 Hz. The experiment was run on a Dell Optiplex 7020 PC (processor, Intel Core i7-4790 running at 3.6 GHz; operating system, Windows 7) with a ViewSonic XG2402 24-inch monitor (resolution, 1024 x 768; refresh rate, 144 Hz). Participants were seated 60 cm away from the monitor. Stimuli were single-line sentences presented on the center-left of the screen. Chinese text was displayed in black on grey using the font SimSun (size 30). Each character equaled 1.6° of visual angle. Display changes took an average of 7 ms to complete after the participants' eyes crossed the invisible pre-target boundary.

4.3.4 Procedure

Each participant performed a 5-point calibration and validation of the eye-tracker before beginning the experiment and at the beginning of the second block. Drift correction was

performed before each sentence. Participants were asked to try to understand each sentence they read and were presented with a simple yes-no comprehension question after 16 out of 80 randomly selected sentences to encourage them to read for meaning (responses were not recorded and not used for analysis). Sentences were presented in random order. Participants were given an opportunity to rest after 40 sentences, after which the calibration and validation process was repeated. A practice block of five sentences was carried out at the beginning of the experiment to ensure that all participants were familiar with the experimental procedure. The full experimental session lasted around 30 minutes.

4.3.5 Data analysis

Inferential statistics were based on planned comparisons of the identical and sign phonologically related preview conditions with the unrelated preview as the reference condition. Analyses included three dependent variables: FFD, GD, and TRT. Data was filtered following a procedure similar to Chiu and Wu (2016). Four percent of trials from Study 1 (i.e., for hearing readers) and 3% from Study 2 (i.e., for deaf readers) were discarded due to blinks, movements, skipping, or machine failure. Trials in which the pre-target word was skipped were discarded (hearing: 15% of data; deaf: 16% of data). Any trials with FFDs under 100 ms or GDs over 1500 ms were also discarded (hearing: 4% of data; deaf: 3% of data). Additionally, any trials where TRTs on targets exceeded 2000 ms were discarded (hearing: 1% of data; deaf: 2% of data). For Study 1, 1877 observations (78% of data) for FFD/GD and 1853 observations (77% of data) for TRT contributed to the analysis of hearing readers. For Study 2, 1954 observations (79% of data) for FFD/GD and 1915 observations (77% of data) for TRT contributed to the analysis of deaf readers.

Data were analyzed in R (Team, 2014) with the lme4 package (Bates et al., 2012). We used generalized linear mixed-effects models (GLMMs) with a Gamma distribution and an identity link between predictors and dependent variables so as to avoid log-transforming our data, which was positively skewed (see Lo & Andrews, 2015 for a detailed discussion of this approach to statistical analysis in mental chronometric research). Statistical models

were built for Study 1 and Study 2 following the same procedure for each dependent variable (FFD, GD, and TRT).

In order to see if there was a dominant effect of sign phonological relatedness reflecting the findings of either Pan et al. (2015) or Chiu and Wu (2016), the first set of models treated the sign phonologically related condition as a single variable, regardless of whether the sign translation pairs were of the HLM, HL, HM, or LM sign phonological configurations. To test our specific hypotheses regarding how specific sign phonological parametric configurations might modulate parafoveal preview effects, we built a second set of models that expanded the sign phonologically related condition into four separate variables: (1) sign-related translation pairs that overlap in handshape, location, and movement (HLM pairs); (2) pairs that overlap in handshape and location (HL pairs); (3) pairs that overlap in handshape and movement (HM pairs); and (4) pairs that overlap in location and movement (LM pairs).

Models with maximal random structure did not converge because of overparameterization, so random structure was reduced to by-participant and by-item random intercepts (Baayen et al., 2008). The formula used for our models was specified as follows: (Eye-Tracking Measure) $\sim$ Preview Condition + (1 | Participant) + (1 | Item). Absolute t -values at or above 1.96 indicate statistical significance at the 0.05 alpha level. As our deaf participants varied in terms of their age of HKSL acquisition, a factor that can affect sign processing (Carreiras, 2010), we set up additional models which included participants' age of HKSL acquisition as a fixed effect to see if it interacted with any of the preview conditions.

4.4 Results

Full summaries of normed means per condition from the raw data for Study 1 and Study 2 are presented for each eye movement measure in Table 4.2 and Table 4.3, respectively. All GLMMs can be found in Appendix 3 (Tables 6.7, 6.8, 6.9, 6.10, and 6.11).

4.4.1 Study 1: Hearing readers

In Study 1, there was a significant preview benefit associated with identical previews across the three dependent variables for hearing readers (FFD: $b = -51.04$, $SE = 5.12$, $t = -9.97$; GD: $b = -89.61$, $SE = 6.71$, $t = -13.35$; TRT: $b = -166.56$, $SE = 11.18$, $t = -14.90$), but no overall effect of sign translation previews [all $\text{abs}(t\text{-values}) \leq 1.22$]. As expected, the second set of models also showed no significant effects associated with sign phonological relatedness in the HLM, HL, HM, or LM conditions [all $\text{abs}(t\text{-values}) \leq 1.58$]. Results are visualized in Figure 4.3a (FFD), Figure 4.4a (GD), and Figure 4.5a (TRT). These results indicate that sign translation previews do not bring about preview benefit or preview cost effects in non-signing hearing readers.

	Identical Preview	Overall Sign Preview	HLM Sign Preview	HL Sign Preview	HM Sign Preview	LM Sign Preview	Unrelated Preview
FFD (ms)	218 (4)	283 (6)	288 (14)	278 (10)	270 (11)	294 (11)	275 (5)
GD (ms)	263 (6)	366 (10)	371 (19)	356 (16)	370 (20)	368 (16)	362 (9)
TRT (ms)	417 (13)	603 (15)	609 (25)	596 (26)	597 (27)	611 (26)	617 (15)

Table 4.2: *Eye-tracking measures for hearing readers in Study 1.* Normed means for all eye-tracking measures (FFD = first fixation duration; GD = gaze duration; TRT = total reading time) in milliseconds for each preview condition with standard errors in parentheses. Mean fixation times for the sign phonologically related previews are divided by sub-condition in the HLM/HL/HM/LM Sign Preview columns and collapsed together in the Overall Sign Preview column. H = handshape. L = location. M = movement.

4.4.2 Study 2: Deaf readers

In Study 2 there was a significant preview benefit for deaf readers in the identical condition across all three dependent variables (FFD: $b = -27.54$, $SE = 4.71$, $t = -5.85$; GD: $b = -49.37$, $SE = 6.26$, $t = -7.88$; TRT: $b = -138.97$, $SE = 8.25$, $t = -16.85$). There was no overall effect of the sign phonologically related condition when the HLM, HL, HM, and LM preview types were treated as a single variable [all $\text{abs}(t\text{-values}) \leq 1.06$]. However, preview effects emerged in the second set of models which included the four sign phonologically related sub-conditions. In FFD (Figure 4.3b), there was a significant

preview cost effect of HM sign translation previews of around 17 ms ($b = 16.62$, $SE = 6.93$, $t = 2.40$) but no significant effects of the HLM ($b = 3.49$, $SE = 7.38$, $t = 0.47$), HL ($b = 0.93$, $SE = 6.58$, $t = 0.14$), or LM ($b = -3.76$, $SE = 6.69$, $t = -0.56$) sign translation previews. In GD (Figure 4.4b), a significant preview benefit of approximately 18 ms emerged in the HL preview condition ($b = -17.54$, $SE = 8.94$, $t = -1.96$) and significant preview cost, also around 18 ms, for the HLM condition ($b = 18.20$, $SE = 9.05$, $t = 2.01$). The HM preview cost effect remained significant in GD ($b = 37.86$, $SE = 11.72$, $t = 3.23$), reaching approximately 38 ms. There was no significant effect associated with LM previews in GD ($b = -2.88$, $SE = 9.18$, $t = -0.31$). In TRT (Figure 4.5b), there was significant preview benefit of about 40 and 26 ms for HL ($b = -39.99$, $SE = 9.88$, $t = -4.40$), and LM previews ($b = -25.83$, $SE = 9.83$, $t = -2.63$) respectively and significant preview cost of 43 and 47 ms for HLM ($b = 43.48$, $SE = 9.88$, $t = 4.40$) and HM ($b = 46.91$, $SE = 10.46$, $t = 2.63$) previews respectively.

Interactions between age of HKSL acquisition and the identical preview condition approached significance in FFD ($b = 2.29$, $SE = 1.25$, $t = 1.83$), GD ($b = 2.81$, $SE = 1.70$, $t = 1.66$), and TRT ($b = 4.99$, $SE = 2.61$, $t = 1.91$), suggesting that participants who learned HKSL later might have benefited less from identical previews. In TRT, age of HKSL acquisition interacted significantly with the unrelated preview condition ($b = -15.74$, $SE = 7.76$, $t = -2.03$) which indicates that later learners of HKSL were less disrupted by unrelated previews. Age of HKSL acquisition did not interact significantly with any of the sign phonologically related conditions [all $\text{abs}(t\text{-values}) \leq 1.58$].

4.5 Discussion

The aim of this study was to investigate how the different overlapping sign phonological parameters associated with sign translation previews affect parafoveal processing in deaf signers of Hong Kong Sign Language. To do this, we used a parafoveal preview paradigm in which participants read sentences in three different preview conditions: identical, sign

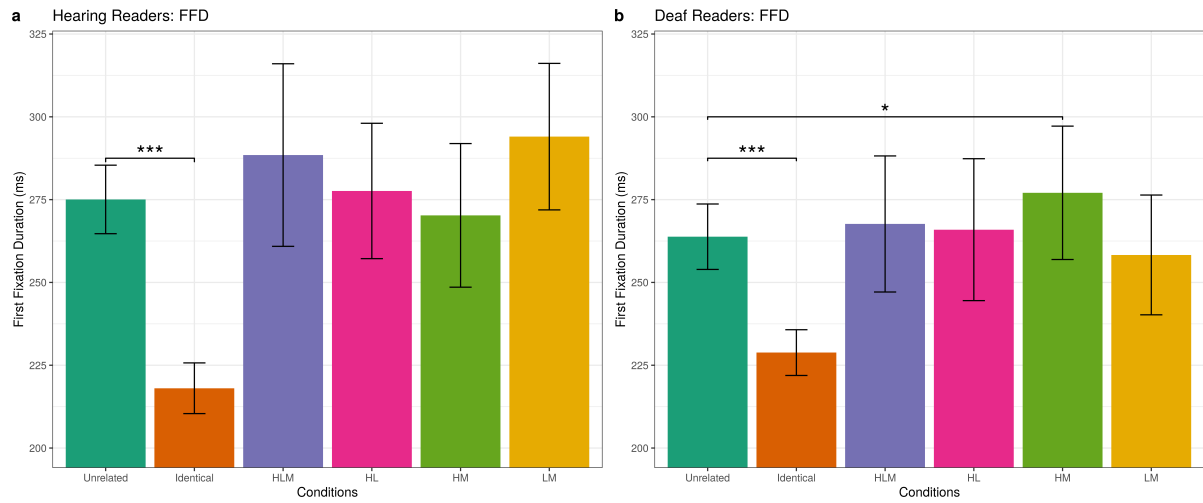


Figure 4.3: *Study 1 and Study 2 first fixation durations.* Average first fixation durations (FFDs) in milliseconds for each condition. Hearing reader data (Study 1) shown in Figure 4.3a. Deaf reader data (Study 2) shown in 4.3b. Stars denote level of statistical significance based on estimated p-values produced by the lmerTest package in R (Kuznetsova et al., 2017). Error bars show 95% confidence intervals. H = handshape. L = location. M = movement.

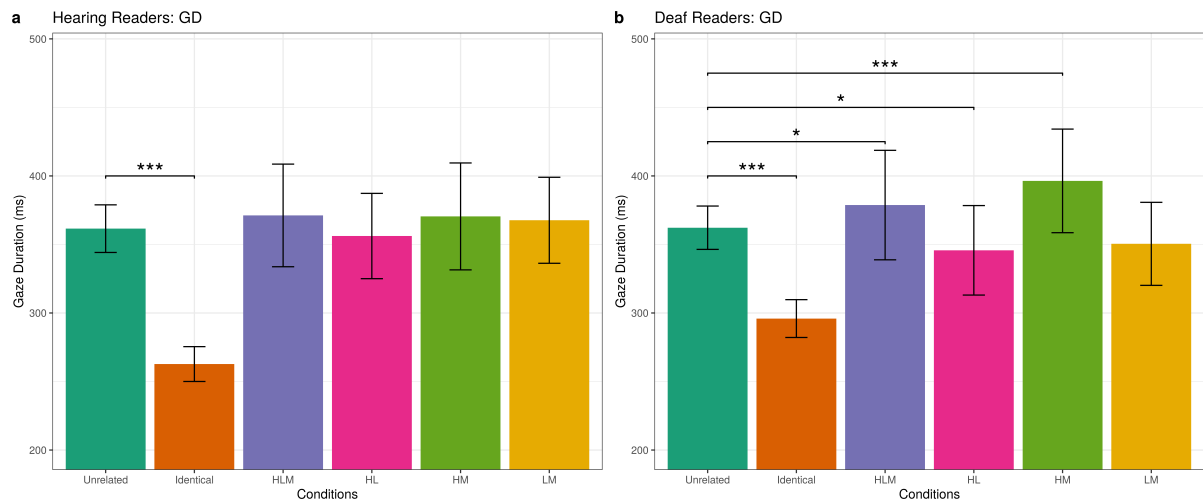


Figure 4.4: *Study 1 and Study 2 gaze durations.* Average gaze durations (GDs) in milliseconds for each condition. Hearing reader data (Study 1) shown in Figure 4.4a. Deaf reader data (Study 2) shown in 4.4b. Stars denote level of statistical significance based on estimated p-values produced by the lmerTest package in R (Kuznetsova et al., 2017). Error bars show 95% confidence intervals. H = handshape. L = location. M = movement.

	Identical Preview	Overall Sign Preview	HLM Sign Preview	HL Sign Preview	HM Sign Preview	LM Sign Preview	Unrelated Preview
FFD (ms)	229 (4)	267 (6)	268 (10)	266 (11)	277 (10)	258 (9)	264 (6)
GD (ms)	296 (7)	367 (10)	379 (20)	346 (17)	396 (19)	350 (15)	362 (9)
TRT (ms)	519 (15)	691 (16)	742 (31)	643 (27)	711 (31)	675 (27)	675 (15)

Table 4.3: *Eye-tracking measures for deaf readers in Study 2.* Normed means for all eye-tracking measures (FFD = first fixation duration; GD = gaze duration; TRT = total reading time) in milliseconds for each preview condition with standard errors in parentheses. Mean fixation times for the sign phonologically related previews are divided by sub-condition in the HLM/HL/HM/LM Sign Preview columns and collapsed together in the Overall Sign Preview column. H = handshape. L = location. M = movement.

phonologically related, and unrelated. The sign phonologically related condition had four sub-conditions divided according to which sign phonological parameters were shared by the preview and target: sign translation preview-target pairs that overlapped in handshape, location and movement (HLM); pairs that overlapped in only handshape and location (HL); pairs that overlapped in only handshape and movement (HM); and pairs that overlapped in only location and movement (LM). Based on the findings of past research, we expected to see either of two patterns: (1) HLM, HL, and LM pairs would be associated with preview cost due to their overlap in the location parameter while preview benefit would be found associated with HM pairs; or (2) a greater degree of parametric overlap would result in preview cost while a lesser degree of overlap would be associated with preview benefit, such that we would find preview cost associated with HLM pairs and benefit with HL, HM, and LM pairs.

In Study 1, we ran our experiment with a group of hearing readers who had no previous knowledge of sign language. As expected, we found significant preview benefit in the identical condition but no significant effects associated with the sign phonologically related conditions. This suggests that significant effects of sign phonologically related previews among deaf readers are not likely attributable to spoken-phonological, orthographic, or semantic preview effects (or some other uncontrolled factor). In Study 2, as expected, we found significant effects associated with the HLM, HL, HM, and LM previews among the deaf readers. Given the findings of Study 1, these results strongly

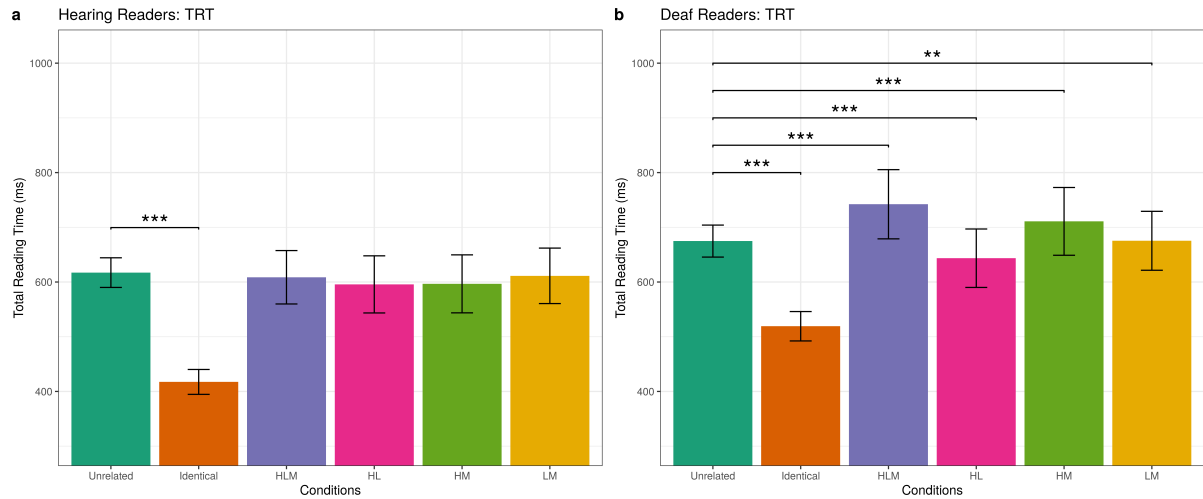


Figure 4.5: *Study 1 and Study 2 total reading times.* Average total reading times (TRTs) in milliseconds for each condition. Hearing reader data (Study 1) shown in Figure 4.5a. Deaf reader data (Study 2) shown in 4.5b. Stars denote level of statistical significance based on estimated p-values produced by the lmerTest package in R (Kuznetsova et al., 2017). Error bars show 95% confidence intervals. H = handshape. L = location. M = movement.

suggest that Hong Kong deaf readers activate HKSL during Chinese sentence reading.

Based on previous parafoveal preview and sign perception research (e.g., Carreiras et al., 2008, Orfanidou et al., 2009, Pan et al., 2015), one prediction we made was that the location parameter would be associated with preview cost during reading. However, our findings did not reflect this. In FFD, there was early preview cost associated with HM previews. In GD, preview cost was associated with both HM and HLM previews, while a significant preview benefit emerged for HL previews. In the late measure of TRT, there was significant preview cost in the HLM and HM conditions and significant preview benefit in the HL and LM conditions. Therefore, location overlap did not appear to lead to cost effects. The second possibility we raised was that higher degrees of sign phonological similarity would result in preview cost, while lesser degrees would result in benefit. This was partially reflected by the data in that we did see preview cost associated with HLM pairs, which overlapped in all three parameters—a finding in line with D. P. Corina et al.’s (2006) conclusion that overlap on more than two parameters is more likely to lead to inhibition in sign perception tasks. However, HM sign translation previews also led to

preview cost despite only overlapping in two parameters. Furthermore, when participants were asked to subjectively rate how similar they felt sign translation pairs were in terms of their sign phonology, HM pairs were not rated as significantly more similar than HL pairs, which, given the finding that HL pairs led to preview benefit, suggests that overall sign phonological similarity of translation pairs is not the only factor determining whether previews will result in cost or benefit.

As neither of our predictions fully aligned with our results, other factors pertaining to the sign phonological sub-conditions are likely to be involved in the modulation of parafoveal preview effects. If we first look at the strength and time course of preview effects, momentarily disregarding the direction of those effects (i.e., whether they were associated with preview cost or preview benefit), we see that only HLM, HM, and HL sign translation pairs brought about preview effects in early processing (measured by FFD and GD). The effects of LM previews only became significant in TRT, which reflects late processing as it includes the durations of regressive fixations during re-reading. The fact that all significant effects in FFD and GD overlapped in handshape suggests that the handshape parameter is of special importance for sign activation via orthography and required for early activation of sign phonology during reading. Interestingly, the special status of handshape was also reflected in the results of our sign phonological similarity judgment task, which had participants rate how phonologically similar they thought each Chinese word pair was based on their HKSL translations. Their responses suggested that handshape was particularly important for HKSL signers as pairs that only overlapped in movement and location were rated as being significantly less similar than the three other parametric configurations, all of which overlapped in handshape. The finding that handshape overlap strengthens sign phonological activation during reading was also attested to in Morford et al. (2019). Taken together, this strongly points to the handshape parameter being of special importance in sign activation processes during reading.

While handshape appears to be necessary for early sign activation to occur in reading,

handshape itself did not determine whether sign translation previews were more likely to lead to preview cost or preview benefit. Preview cost, in fact, required simultaneous overlap in both the handshape and movement parameters, which was demonstrated by our finding of early and late preview cost in the HLM and HM sign phonological sub-conditions. This pattern of results indicates that handshape, together in combination with the movement parameter (considered the nucleus of a sign syllable—Wilbur, 2011), plays an important role in the sign activation processes spurred by exposure to the orthography of the relevant Chinese translation. A possible explanation for the resulting preview cost is that, when both members of the sign translation preview-target pair overlap in the parameters of handshape and movement, a high degree of competition is created between the conflicting lexical representations activated by the preview and target. Thus, subsequent fixation times on the target are longer as more time is needed to resolve this conflict and integrate the correct target into the sentence.

This finding, which gives special status to the parameters of handshape and movement, seems to diverge from psycholinguistic studies on sign perception which have found the location parameter to be uniquely associated with inhibitory priming effects (e.g., Carreiras et al., 2008, Orfanidou et al., 2009). This divergence in findings is unsurprising, however, if the activation of sign phonology via orthography, as proposed by Quandt and Kubicek (2018), involves the recruitment of the brain’s sensorimotor system in an action simulation process of the sign. It is likely that certain features unique to different sign phonological parameters, such as the high visual saliency of location, would be unlikely to affect cognitive processing during reading in the same way as they do during sign perception. The contention that cognitive processes involved in sign activation and sign perception are distinct in nature has been supported by brain research that has shown that viewing signs in real time, as opposed to simulating them mentally, has not been found to activate action mirroring processes in deaf signers (Emmorey et al., 2010).

Interestingly, contrary to what we would expect based on the studies of sign perception mentioned above, the unique property of the location parameter revealed by the results

of this study was, in fact, its association with preview benefit, which was only observed when sign translation pairs overlapped in location plus a single additional parameter—either handshape or movement. This suggests that the co-presence of location and one additional parameter can activate the target, along with any other signs sharing those parameters, without (in contrast to HLM and HM pairs) creating a degree of competition high enough to lead to preview cost (see discussion of the impact of sign similarity on lexical activation in D. P. Corina & Knapp, 2006). One study on sign perception, Dye and Shih (2006), also found facilitative priming associated with overlapping location and movement. However, it is difficult to interpret this alignment in findings regarding the facilitative effects associated with location and movement overlap given that (1) as discussed, it is not clear how comparable sign activation during reading and sign perception processes are, and (2) most other studies on sign perception have not found this same result.

Pan et al. (2015) attributed their finding of preview cost to depth of lexical access. They suggested that in readers with efficient parafoveal processing abilities, a deep level of lexical access can be achieved when parafoveal processing time is longer due to extended fixations on the pre-target region. As lexical access deepens, features of the preview are more fully activated, which leads to a high level of competition between the lexical representations activated by the preview and target and a subsequent disruption of target processing. To check if parafoveal processing time might have influenced our pattern of results, we extended our GLMMs to include gaze durations on pre-target words as a fixed effect. These extended models only revealed one significant interaction between pre-target and target GDs in the LM condition ($b = -0.13$, $SE = 0.06$, $t = -1.99$), suggesting that GDs on targets following LM previews actually became shorter with longer pre-target fixations. This is, in fact, the opposite of the positive correlations between pre-target and target fixation times that we would expect if the preview cost found in our study was mainly a result of deep lexical access and suggests that deep lexical access is not the only factor involved in bringing about preview cost. For deaf readers, the overlapping

parameters in sign translation preview-target pairs clearly play an important role such that certain overlapping sign phonological features (handshape and movement in our study) lead to higher degrees of competition, and thus are more likely to disrupt target processing time. The interference effects in our study might suggest that signs overlapping in handshape and movement are closely associated in the mental lexicons of HKSL signers, possibly due, at least in part, to their perceived similarity. Chiu and Wu (2016) were correct in their hypothesis that certain sign parameters might have different effects on parafoveal processing, but their finding of preview benefit might not be attributable to the handshape parameter alone as they suggested. Rather, if a large number of their preview-target pairs overlapped in only handshape and location, it is possible that this was the reason for their finding of preview benefit. Alternatively, it is possible that these parameters might not have the same effects for signers of different sign languages such as Taiwanese Sign Language (the native sign language of their participants). More research is needed in different deaf communities to better understand whether sign phonological parameters affect parafoveal processing the same way across different groups of signers.

As the deaf participants in our study varied widely in terms of their age of HKSL acquisition, we built an additional set of models to look at whether the age of sign language acquisition influenced parafoveal processing effects among our deaf readers. Including age of acquisition as a fixed effect in our models, though, did not significantly improve fit, and there were no significant interactions between any of the sign phonologically related conditions. However, there was an interesting pattern which is worth discussing. In FFD, GD and TRT, interactions between age of HKSL acquisition and the identical condition were close to significant, a consistent pattern suggesting that participants who acquired HKSL later in life benefitted less from identical previews. Furthermore, significant interactions between age of acquisition and the unrelated condition indicated that unrelated previews were less disruptive to those who acquired HKSL later in life. As age of HKSL acquisition and reading fluency scores were not correlated in our group of deaf participants [$r(29) = .11, p > .1$], it is not likely that this finding can be attributed to

differences in reading skill. Past parafoveal preview studies on both English and Chinese reading have found that deaf signers have enhanced parafoveal range of vision and can more efficiently process parafoveal previews than hearing non-signers (Bélanger et al., 2013; Bélanger, Slattery, et al., 2012; M. Yan et al., 2015). Our finding that deaf readers with a higher age of acquisition seemed to benefit less from identical previews and be less disrupted by unrelated previews suggests that deaf readers exposed to sign language later in life have weaker parafoveal processing skills and thus are less affected by the content of the preview word. It is possible that early exposure to sign language is important for developing these enhanced parafoveal processing skills. However, as this pattern was relatively weak in our study, more research is needed to support this.

One important implication of our study is methodological. We found that preview effects first emerged in FFD and continued into TRT, at which point they were significant across all four sign phonologically related preview types. In contrast, Pan et al. (2015) found a significant effect of sign phonological previews in FFD that diminished to only a marginal effect in GD and no significant effect in TRT. Like Pan et al.'s (2015) stimuli, all our sign phonologically related previews overlapped in at least two parameters, so we had expected we might also see a comparable overall effect of all sign phonological previews when analyzed together as a single variable. However, in our first set of models, we found no significant effects associated with the collapsed sign phonologically related condition, suggesting that varying preview cost and benefit effects associated with the four sub-conditions led to null preview effects when treated as a single variable. Thus, to avoid obscuring interesting and significant patterns in the data, it appears to be important that researchers design stimuli such that sign translation preview-target (or prime-target) pairs are uniform in terms of their overlapping sign phonological parameters.

An important point to note is that our findings from the sign relatedness survey did not coincide with the findings of Hildebrandt and Corina (2002), who found that signers of American Sign Language categorize signs sharing a common location and movement as more similar than those sharing handshape and location or handshape and movement.

One possibility that might explain these diverging results is that intuitions regarding phonological similarity of signs vary across different sign language communities. Alternatively, it is possible that our task, which had participants read the written Chinese translations of each pair and reflect on their own signing rather than watch recordings of the signs being produced, tapped into a different set of linguistic intuitions. This fact that would be unsurprising given that we have already seen that sign perception and sign activation during reading bring about different patterns of brain activity (see Emmorey et al., 2010, Quandt & Kubicek, 2018). In either case, more research on deaf readers from different language backgrounds would be valuable for unpacking this issue.

One limitation of our study was that, due to a number of practical constraints, the hearing reader group in Study 1 comprised hearing university students who were more fluent overall than our deaf readers. As the two groups had different baseline reading speeds, we did not directly compare them in a single statistical model, instead using Study 1 to verify a lack of effect among hearing non-signers and support our claim that sign activation is the cause of the pattern among deaf participants. Given that the two groups differed in fluency level and that sentence frames, by necessity, differed across the sign phonologically related sub-conditions, it might be argued that the pattern of results found among deaf participants was due to some of them having higher sensitivity to differences in sentence difficulty. This seems unlikely, however, as sentence frames and preview-target word pairs were well controlled across most relevant measures including sign phonologically related sub-conditions in terms of preview position, sentence length, stroke count (at both the word and sentence level), number of uncommon words, as well as frequencies of target and non-target words. Furthermore, in a post-hoc examination of the data, we found that including reading fluency test scores in our models to control for reading fluency did not affect our overall pattern of results, suggesting that the preview effects we observed are unlikely to be due to variations in reading fluency across the group.

Our results suggest that sign phonological parameters modulate parafoveal preview

effects during Chinese sentence reading in deaf signers of HKSL in a few notable ways. Early sign phonological activation in FFD and GD appeared to require that handshape was among the overlapping parameters in the sign translation preview-target pairs, suggesting that this sign phonological parameter is particularly important in sign activation processes during reading. The co-presence of handshape and movement overlap in sign translation preview-target pairs led to early preview cost, due to overlap of these two parameters leading to stronger activation of the competing lexical representations associated with the preview and target words. In contrast, overlap in location along with either handshape or movement led to early preview benefit, which might suggest that overlap in these two parametric configurations can facilitate activation of the target while not leading to a high degree of competition between activated representations. In sum, the findings of this study suggest that different sign phonological parameters have different effects on parafoveal processing during reading, and, as such, researchers should control for the parameters of sign phonological overlap in sign translation preview-target pairs in future studies on sign activation.

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4.7 Supplementary material

Data and R scripts associated with this article can be found at <https://doi.org/10.5281/zenodo.3600959>.

Chapter 5

The time course of Cantonese and Hong Kong Sign Language phonological activation: An ERP study of deaf bimodal bilingual readers of Chinese (under review)

Abstract

This study aimed to investigate orthographic, spoken phonological, and sign phonological processing among deaf bimodal bilingual readers of Chinese from Hong Kong. To do this, two sentence-reading experiments using an error disruption paradigm were conducted. Sentences were designed to be high-constraint so that contextual information would prime readers to anticipate the final character. Experiment 1 included four types of sentence-final character error: orthographic error, homophonic error, mouth-shape-based error (i.e., “homovisemic error”), and unrelated error. Experiment 2 included two types of sentence-final character error: sign phonologically related error and unrelated error. In Experiment 1, there were significant effects of orthographic and homophonic error types in the N400

window. N400 amplitudes were reduced for orthographic error types, suggesting that orthographic representations were facilitating lexical access. N400 amplitudes were increased in the right central electrodes, which indicated that readers were activating Cantonese phonological representations, though this appeared to result in lexical interference rather than facilitation. In Experiment 2, there was a significant reduction in P200 amplitudes in the left anterior electrodes among deaf readers in the sign phonological condition. Brain activity appeared to reflect competition between the lexical representations activated top-down via context and bottom-up via the sign phonologically related character error. In sum, the results of Experiment 1 and Experiment 2 suggest that, when reading high-constraint sentences, the P200 component is modulated by sign phonology, while the N400 is modulated by orthography and spoken phonology in deaf readers. Based on this, the early effects of sign phonology and later effects of spoken phonology may indicate that, for deaf readers, sign phonology plays an important role in the initial access of word meanings, while spoken phonology is involved in facilitating comprehension during later integrative processes.

5.1 Introduction

Research on deaf bimodal bilinguals, who know both a signed and spoken (or written) language, has formed a complex picture of deaf reading processes with regards to their use of phonological code. For example, there is evidence that bimodal bilingual deaf readers can activate both spoken phonological representations (Gutierrez-Sigut et al., 2017; Hanson & Lichtenstein, 1990; Thierfelder, Wigglesworth, et al., 2020a; M. Yan et al., 2015) and sign phonological representations (Chiu et al., 2016; Chiu & Wu, 2016; Kubus et al., 2015; Meade et al., 2017; Morford et al., 2011; Pan et al., 2015; Thierfelder, Wigglesworth, et al., 2020b) associated with the words they are reading.

Researchers have explicated phonological processes in deaf readers using cognitive models. Elliott et al. (2012), for example, extended the dual-route model (Coltheart

et al., 2001; Coltheart, 2005, 2006) to describe spoken phonological activation in deaf reading, proposing the dual-route cascaded model of reading by deaf adults. The original dual-route model suggests that meaning can be accessed via either (1) a direct route, by which word means are accessed through orthographic representations activated from the text, or (2) an indirect route, whereby orthography activates a word's phonological representation, which, in turn, activates its meaning. Elliott et al. (2012) proposed that deaf readers differ from hearing readers in that their phonological units are based on mouth shapes, or *visemes*, which they acquire through lipreading. Thus, for deaf readers, when the indirect phonological route to meaning is utilized, they access the semantic system through visemic representations rather than the more detailed sound-based phonological representations used by hearing readers. Another model, the deaf bilingual interactive activation model (based on the BIA+ model—see Dijkstra & Van Heuven, 2002), was proposed by Ormel et al. (2009). According to this model, when deaf readers recognize a written word, its sign translation equivalent is automatically activated. In turn, the sign phonological features (i.e., information about the handshape, movement, location, and orientation of the hands) associated with that translation are activated as well. Once the associated phonological features are activated, other signs that share one or more of those sign phonological features are also activated.

While models like these are useful for describing certain aspects of spoken and sign phonological activation in deaf readers, the relationship between these spoken and sign phonological systems is still unclear. For example, we do not know if deaf readers tend to activate one type of code more than the other, nor do we know if these codes are activated simultaneously or during different stages of processing. The goal of the present study is to examine this issue through two Chinese reading experiments focused on adult deaf readers from Hong Kong. Experiment 1 investigates orthographic and spoken phonological processing, and Experiment 2 investigates sign phonological processing.

5.1.1 Chinese Reading

As the current study focuses on Chinese reading, this section will describe some distinguishing characteristics of Chinese script that are relevant to the current study. In the Chinese writing system, a single Chinese character maps to a single syllable, and there are no components within a character that correspond to individual phonemes in the way that letters do in alphabetic writing systems like English. While Chinese characters often contain semantic and phonetic components, which convey information about the meanings and pronunciations of characters, this information is generally unreliable (Gao et al., 1993). In Chinese, it is common for characters that are unrelated in orthography to have the same pronunciations (e.g., 青 /cing1/¹[green] and 稱 /cing1/ [call]). Similarly, many characters that look similar in orthography are entirely different in pronunciation and meaning (e.g., 未 /mei6/ [not yet] and 末 /mut6/ [end]).

Given the considerable differences between Chinese and alphabetic writing systems, we might question whether models, such as the models described above, which have mostly been used to describe reading in English and other languages that are written in alphabetic scripts, can be used to describe Chinese reading processes. Addressing this issue, C. A. Perfetti et al. (2005) argued that reading processes in Chinese and alphabetic writing systems are similar in that, when we read a word in an alphabetic or non-alphabetic language, we automatically activate the orthographic, phonological and semantic representations associated with that word. However, phonological activation in alphabetic languages can begin at the level of the phoneme, while phonological activation in Chinese can only occur at the level of the full syllable. According to C. A. Perfetti et al. (2005), phonology is important in reading, regardless of the specific script being read, because it aids not only in identifying word meanings, but also in post-lexical memory and comprehension processes.

¹Cantonese pronunciations are written in the Jyutping romanization system.

5.1.2 Eye fixations

Error disruption paradigm. Investigating phonological activation in reading requires sensitive measures of cognitive processing, such as eye fixation times. One paradigm that has been used with eye-tracking to investigate phonological activation in deaf and hearing readers of Chinese is the error disruption paradigm. In these studies, participants read sentences in which correct target characters were replaced with orthographically related or homophonic character errors. When fixation times on orthographically related or homophonic errors are found to be shorter than those on unrelated errors, which serve as controls, it is taken to mean that word meanings are being accessed through orthographic or phonological representations, respectively. Eye-tracking studies on adult hearing readers of Chinese have consistently found that they access word meanings primarily through orthographic representations in early processing, but that phonological activation plays a role in late processing (Feng et al., 2001; Wong & Chen, 1999; Zhou et al., 2018). There is some evidence, though, that earlier phonological activation can be facilitated by high levels of contextual constraint (Thierfelder, Durantin, et al., 2020; Thierfelder, Wigglesworth, et al., 2020a).

In one study that used an error disruption paradigm with eye-tracking has focused specifically on adult deaf readers of Chinese, Thierfelder, Wigglesworth, et al. (2020a) investigated how deaf readers use orthographic, spoken phonological, and mouth-shape based (i.e., *visemic*) code during reading. In this study, participants read sentences in which correct targets (e.g., 自然 /zi6 jin4/ [natural]) were manipulated to contain an orthographic error (e.g., 目 /muk6/ [eye] substituting 自 /zi6/ [self]), a homophonic error (e.g., 字 /zi6/ [word]), a homovisemic error (e.g., 示 /si6/ [word]), or an unrelated error (e.g., 分 /fan1/ [divide]). Homovisemic errors were errors that were phonologically distinct from correct targets and homophonic errors but contained phonological differences that would not be easily perceived through lipreading. For example, the characters 自 /zi6/ [self] and 示 /si6/ [show] sound different to Cantonese speakers, but because they only differ in voicing of the onset, a deaf person relying on lipreading would not be able

to distinguish them based on the mouth shapes/movements of someone pronouncing the words aloud. In contrast, the characters 自 /zi6/ [self] and 分 /fan1/ [divide], read aloud, could be easily distinguished visually by visible differences in articulation.

The results of Thierfelder, Wigglesworth, et al. (2020a) showed that deaf readers mainly accessed word meanings through orthographic representations, but that spoken phonological representations were activated in early processing when the contextual predictability of target words was high and among deaf readers with high levels of reading fluency. Furthermore, there was evidence that deaf readers were activating visemic representations in the eye-tracking measure of total reading time (the total length of all fixations on a target, including regressive fixations made when returning to re-read a target) as a late error recovery strategy. Furthermore, deaf readers with lower reading fluency levels might have been activating phonology based on visemes in early processing when contextual constraint was high. These findings lent some support to Elliott et al.'s (2012) dual-route cascaded model of reading by deaf adults in that it suggested some limited use of visemic code, though only limited to certain circumstances (i.e., re-reading for error recovery) or readers (i.e., lower fluency deaf readers).

Parafoveal preview paradigm. Chinese readers have a perceptual span that encompasses around one character to the left and three characters to the right of the current fixation (Inhoff & Liu, 1998). Characters beyond the fixated word, therefore, can also affect cognitive processing during reading. The parafoveal preview paradigm, or boundary paradigm (Rayner, 1975), has been used to investigate this phenomenon (see Schotter et al., 2012, as well as Vasilev & Angele, 2017, for overview). In this paradigm, a target word, which is preceded by an invisible boundary, is substituted with preview word. As the reader's eyes cross the invisible boundary, the preview word is instantaneously replaced by the correct target word. This display change is often unnoticed by the reader as it occurs during the saccade between the pre-target and target words. Studies on Chinese reading have found that when preview words are orthographically or phonologically similar to targets, target fixations tend to be shorter in duration relative to unrelated

preview words, which serve as controls (Tsai et al., 2012; Tsai et al., 2004; M. Yan et al., 2009). This facilitation of processing speed by the contents of the preview word is referred to as *preview benefit*. Related preview words can, in some instances, have the opposite effect, incurring *preview cost*. For example, Pan et al. (2016) and M. Yan et al. (2015) found that fixations on targets were longer after semantically related previews than they were after unrelated previews, suggesting that competition between the related meanings of the preview and target interfered with processing.

The parafoveal preview paradigm has been used to investigate sign phonological activation during reading by using preview-target pairs that, when translated into the native sign language of the reader, are related in terms of their sign phonological structure. Sign phonological relation in reading studies has generally entailed overlap in two or more sign phonological parameters, following Morford et al. (2011). The three main phonological parameters of a sign were initially identified as its handshape, location, and movement (Stokoe et al., 1965). Hand orientation, as well as facial expressions (or *non-manual features*), have been identified as additional parameters, but most research has focused on those of handshape, location, and movement.

Pan et al. (2015) was the first to carry out a parafoveal preview study to investigate whether deaf readers of Chinese activated sign phonological representations when reading sentences. They used preview-target sign translation pairs that overlapped in at least two out of four (handshape, location, movement, and orientation) parameters. They found preview cost in first fixation duration (the length of the first fixation on a target, measured in milliseconds) associated with the sign phonologically related condition, which they concluded was due to interference between the conflicting lexical representations activated by the previews and targets. Chiu and Wu (2016) carried out a similar study with deaf readers from Taiwan. All preview-target pairs in their stimuli overlapped in handshape (the extent to which they overlapped on other parameters was unspecified), rather than any two as in Pan et al. (2015). Rather than preview cost, they found evidence of preview benefit emerging in first fixation duration and concluded that the

handshape parameter might be important in facilitating preview benefit. Studies on sign activation in single-word reading tasks have also suggested that different configurations of sign phonological overlap seem to influence whether priming is inhibitive or facilitative (Kubus et al., 2015), as well as the strength of the priming effect (Morford et al., 2019).

To examine this issue in more detail, Thierfelder, Wigglesworth, et al. (2020b) carried out a parafoveal preview study that used four types of sign phonologically related preview, all of which overlapped with targets in two to three sign phonological parameters. HLM pairs overlapped in handshape, location, and movement parameters—that is, they were essentially identical, though they differed in their non-manual features. HL pairs overlapped in handshape and location but differed in movement; HM pairs overlapped in handshape and movement but differed in location. Lastly, LM pairs overlapped in location and movement but were produced with different handshapes. The authors found that parafoveal preview effects from HM previews emerged the earliest, during the first fixation on the target. The effects of HLM and HL previews emerged slightly later in gaze duration (the duration of the first fixation plus the duration of any refixations that occurred on the target before fixating on another word in the sentence), while significant effects of the LM condition emerged latest, in total reading time (the total length of all fixations on a target), when participants were re-reading targets. The authors concluded that the handshape parameter was important for early activation of sign phonology.

Interestingly, they also found that the direction of the effect depended on which sign phonological parameters overlapped between the preview and target. HLM and HM pairs led to preview cost—that is, fixations on correct targets were significantly longer when following an HLM or HM preview than they were following unrelated controls. The effects of HL and LM previews showed the opposite effect, leading to shorter fixations on targets than on unrelated controls. The authors concluded that handshape and movement overlap led to strong competition between the lexical representations associated with the preview and target, and this competition resulted in a processing disruption. This finding may indicate that these two parameters are particularly important for activating word

meanings through sign phonological representations.

The eye-tracking studies discussed above have shown that both spoken and sign phonological activation influence processing during reading in deaf bimodal bilinguals. Taken together, the evidence seems to suggest that the effects of sign phonological activation can emerge as early as the first fixation on a target. However, the effects of spoken phonological activation tend to emerge later—in gaze duration, at earliest, though this was only found in certain circumstances (e.g., when contextual constraint is high or among highly fluent readers).

5.1.3 Event-related potentials

Event-related potentials (ERPs) are useful for investigating the time course of orthographic and phonological activation in reading because they are highly sensitive and provide millisecond-by-millisecond information on brain wave activity. This overview of ERPs will focus on two well-studied ERP components, the P200 and N400. The P200 is a positive ERP wave that peaks around 200 ms after stimulus onset and has been associated with the early extraction of the orthographic and phonological features of words (Barnea & Breznitz, 1998; Sereno et al., 1998). The N400 is a negative ERP wave that peaks around 400 ms after stimulus onset and is known to reflect incongruity between a word and its context (Connolly et al., 1995; Kutas & Hillyard, 1980).

In ERP studies on silent Chinese word and sentence reading, the P200 and N400 components have been associated with each of orthographic, phonological, and semantic processing. Zhang et al. (2009), using semantic and homophone judgment tasks, found phonological effects in the P200 window when character pairs were low-frequency homophones. In the N400, when pairs were high-frequency homophones, they found reduced wave amplitudes reflecting phonological and semantic activation. They also found semantic modulation of the N400 in low-frequency semantically related pairs. Investigating early phonological activation, Kong et al. (2010) carried out a semantic judgment experiment with four conditions: homophonic, rhyming, control, or identical. They found

that relative to controls, homophonic and rhyming primes elicited a larger P200, mainly in the centro-parietal areas. To examine whether orthographic information alone could modulate the P200, Kong et al. (2012) conducted a primed semantic judgment study using orthographically related pairs that were unrelated in terms of pronunciation. The orthographically related pairs elicited reduced P200 amplitudes, indicating that the P200 can be modulated by orthographic similarity.

While the above studies used single-character or word reading tasks, some researchers have conducted sentence reading studies with ERPs using the error disruption paradigm. Ren et al. (2009) created high-constraint sentences with predictable terminal characters. Sentences were manipulated such that the terminal character was substituted with either an orthographic, homophonic, or unrelated error. Orthographic errors were similar in appearance to correct targets but differed in pronunciation, and homophonic errors had the same pronunciation as correct targets but were unrelated in orthography. Correct and unrelated characters were used as the baseline and control conditions, respectively. They found that N400 amplitudes were significantly less negative in the homophonic condition than in the control condition, regardless of whether words were high- or low-frequency. The authors concluded that this is evidence that phonology contributes to the integration of meaning and context in Chinese reading. Liu et al. (2011) conducted a similar error disruption study. In addition to orthographic and homophonic conditions, they included a semantic condition, wherein semantic substitution characters were related to correct targets in meaning but unrelated in terms of orthography and phonology. In the P200 window, they found reduced P200 amplitudes in the homophonic condition, and in the N400 window, post-hoc analysis suggested that N400 amplitudes were smallest for the semantic condition.

Relatively few ERP studies have been done on phonological activation in deaf readers. In a picture-based priming study on deaf readers of Chinese, P. Li et al. (2017) found evidence of spoken phonological activation among deaf readers, which emerged in the N400. However, for hearing readers, this effect emerged earlier in the N200/P200 components.

They concluded that spoken phonological activation for deaf readers was later than for hearing readers. Gutierrez-Sigut et al. (2017) investigated whether deaf readers of Spanish activated Spanish phonology in a masked priming lexical decision experiment. Target words were preceded by either a pseudohomophone prime or an orthographic control prime. They found that N250 and N400 amplitudes were reduced for pseudohomophones relative to controls, suggesting that deaf readers of Spanish do have access to spoken phonological codes. Meade et al. (2017) ran a semantic relatedness judgment experiment with ERPs to investigate whether deaf signers activate equivalent signs from American Sign Language (ASL) during reading. They found that when English prime-target word pairs had sign-phonologically related (sharing at least two sign phonological parameters, such as handshape and location) ASL translations, N400 amplitudes were reduced, while judgement times were longer. They concluded that, while slower RTs in the semantic judgement task reflected sign phonological interference at the task-level, the reduced N400 reflected the initial activation of the sign translation.

These studies show that the ERP technique is useful for investigating the orthographic, as well as spoken and sign phonological processes active during reading. Both orthographic and phonological information have been shown to modulate wave amplitudes of the P200 and N400 components during Chinese reading. The N400 has also been shown to reflect both spoken and sign phonological processing in deaf readers. However, no studies have used ERPs to investigate both spoken and sign phonological processing in deaf readers of Chinese.

5.1.4 The Present Study

Evidence from both eye-movement recordings and ERPs have shown that deaf readers can activate spoken and sign phonology during word- and sentence-based reading tasks. However, as these studies have all been done using different paradigms or with deaf readers of different linguistic backgrounds, it is difficult to compare them directly. In Thierfelder, Wigglesworth, et al. (2020b), Hong Kong deaf readers were found to activate

sign phonological code very early, with effects already emerging in the first fixation on the target. In contrast, Thierfelder, Wigglesworth, et al. (2020a) found spoken phonological code to emerge later—in gaze duration (though only in high constraint contexts or among high fluency readers) and total reading time. Taken together, these findings seem to point to the possibility that deaf readers activate sign phonology at an earlier stage of processing than spoken phonology.

In this study, two error disruption paradigms with ERPs are used to investigate the time course of orthographic, spoken phonological, and sign phonological activation during Chinese sentence reading. Experiment 1 focuses on orthographic and spoken phonological activation by including correct, orthographically-related, homophonic, visemic, and unrelated conditions. Experiment 2 focuses on sign phonological activation and includes correct, sign phonologically related, and unrelated conditions. By using a very similar item design for each study, the findings will also give insight into whether or not activation patterns are similar for both spoken and sign phonological code. Based on the findings of Thierfelder, Wigglesworth, et al. (2020b) and Thierfelder, Wigglesworth, et al. (2020a), The hypothesis of this study is that sign phonological effects will emerge early in the P200, while spoken phonological effects will emerge in the N400 window. Given the consistent findings of a strong tendency for deaf readers to activate word meanings through orthographic representations (Bélanger et al., 2013; Thierfelder, Wigglesworth, et al., 2020a; M. Yan et al., 2015). It is also expected that orthographic effects will emerge early in the P200.

5.2 Experiment 1

5.2.1 Method

Participants and background measures

Twenty-four participants with severe to profound hearing loss, ranging 80–120 dB ($M = 102$, $SD = 12$), took part in the experiment. All deaf participants had begun attending an oral deaf school, where lessons were taught primarily in spoken Cantonese, at a young age and were high school graduates. Deaf participants reported that they primarily used HKSL for day-to-day communication but varied widely in terms of when they first began learning it. Eight were native signers with deaf parents or an older deaf sibling, while the latest learner began using HKSL consistently at the age of 13 (though this participant reported some limited exposure prior to that). The average age of HKSL acquisition was four years old ($SD = 4$). Deaf participants ranged in age from 28 to 46 years old ($M = 37$, $SD = 6$). Due to practical limitations, a well-matched hearing comparison group could not be recruited for this study. However, an unmatched sample of 24 hearing university student participants was included to serve as a point of reference to see how expert readers respond to the experimental stimuli. Hearing participants were native speakers of Cantonese and had a mean age of 19 ($SD = 2$) years old. All reported that they had not learned HKSL in the past.

As a measure of reading level, deaf and hearing participants took a Chinese reading fluency test, which was designed based on those described in Moll et al. (2009) and Pan et al. (2011). The test consisted of 85 sentences that progressed from 9 characters in length at the beginning of the test to 20 characters by the end. Twenty-nine of these sentences contained obvious semantic or grammatical errors. Participants were instructed to read the sentences as fast as they could, aiming to read as many as possible within two minutes, while marking each as correct or incorrect. The final reading fluency scores for each participant were calculated as the total number of characters contained within the correctly judged sentences. Scores indicated that deaf participants read at an average rate

of about 146 ($SD = 49$) characters per minute. Hearing participants read at an average rate of 249 characters per minute ($SD = 91$), which ANOVA revealed to be significantly faster than the deaf participants ($p < .001$).

Ethical clearance for this study was granted by the authors' universities, and participants gave written consent before participating in the experiment. All information regarding the study was provided in written Chinese to both groups of participants. Additionally, consent forms and study procedures were explained to deaf participants in HKSL by a fluent signer.

Materials

To construct the stimuli for Experiment 1, twenty-five sets of traditional Chinese characters were selected, each set containing a correct character (e.g., 上 /soeng6/ [above] in 晚上 /maan5 soeng6/ [night]), an orthographically-related character (e.g., 止 /zi2/ [stop]), a homophonic character (e.g., 尚 /soeng6/ [esteem]), a homovisemic character (e.g., 丈 /zoeng6/ [husband]—see below for explanation of how homovisemes were selected) and an unrelated character (e.g., 以 /ji5/ [with]). The five characters in each set were unrelated in terms of meaning. To verify this, HowNet (Dong et al., 2006), a Chinese semantic database for natural language processing that can produce similarity ratings in line with human judgments (Dai et al., 2008), was used to calculate the semantic similarity between each related character with its correct mate. An analysis of variance (ANOVA) showed that there were no differences in semantic similarity across conditions [$F(3, 94) = 0.42$, $p > .1$]. The total number of strokes per character was also matched across conditions [$F(4, 120) = 0.61$, $p > .1$]. Due to the limited number of characters that could be used as orthographic, homophonic, and homovisemic substitutions, these characters tended to be of lower frequency² than the correct characters. Importantly, however, there were no significant differences in frequency across the orthographic, homophonic, homovisemic substitutions, and the unrelated controls [$F(3, 96) = 1.93$, $p > .1$].

²Mean frequencies for both experiments were calculated using the average token count per corpus entry from (H. H. Ho & Kwan, 2001)

For the homovisemic condition, characters were not distinguishable from correct mates through lipreading but differed in their spoken phonology. In English, an analogous example would be the words *mom* and *bomb*, which cannot be distinguished via visual cues on the lips despite their differing pronunciations. As an example from the stimuli, the pronunciations of the character 上 /soeng6/ and its homovisemic mate 丈 /zoeng6/ are easily distinguished by native Cantonese listeners but would be indistinguishable to a deaf interlocutor relying on lipreading. Twenty-three out of 25 homovisemic characters overlapped in rime with their correct mates but differed in onset, while one overlapped in onset but not rime (暫 /zaam6/ as the homovisemic mate to 集 /zaap6/), and one did not fully overlap in either onset or rime (布 /bou3/ as the homovisemic mate to 目 /muk6/; note that this difference is unlikely to be perceived in fluent speech). Nine differed in tone, though tone differences cannot be perceived visually during lip reading (Ching, 1990). The average proportion of phonemes shared by correct characters and the characters in each error condition based on their associated Cantonese Jyutping romanizations are shown in Table 5.1 in the row labeled *Phonemic Overlap*.

Characters in the orthographic condition were chosen based on shared visual similarity with correct targets. A norming study was carried out to assess orthographic relatedness across each set of target characters by asking an independent sample of 20 university students from Hong Kong to judge how similar in appearance the orthographic, homophonic, homovisemic, and unrelated characters were to correct targets on a scale of one (highly dissimilar) to five (highly similar). As expected, there was a significant interaction between condition and orthographic similarity [$F(3, 57) = 121.8, p < .001$]. Characters in the orthographic condition were rated as more similar to their correct mates compared to the other three error types ($ps < .001$), which were not significantly different from each other ($ps > .1$). All character properties are summarized in Table 5.1.

	Correct	Orthographic	Homophonic	Homovisemic	Unrelated
	上	止	尚	丈	以
Example	/soeng6/ [above]	/zi2/ [stop]	/soeng6/ [esteem]	/zoeng6/ [husband]	/ji5/ [with]
Frequency	188 (98)	115 (125)	120 (90)	104 (96)	163 (101)
Orthographic Rating	–	3.6 (1.3)	1.3 (0.6)	1.3 (0.6)	1.4 (0.7)
Phonemic Overlap	–	.12 (.21)	1 (0)	.66 (.15)	.19 (.19)
Semantic Relatedness	–	.36 (.36)	.27 (.29)	.31 (.36)	.31 (.36)
Stroke Count	6.4 (3.7)	6.8 (4.2)	7.9 (3.7)	7.1 (4.9)	6.9 (3.3)

Table 5.1: *Character properties*. *SDs* in parentheses. Mean frequencies from H. H. Ho and Kwan (2001). Semantic similarity calculated using the HowNet (Dong et al., 2006) database.

Each target character was embedded as the second character in a set of four two-character frames—for example, 上 [above] was embedded in 地上 [on the ground], 晚上 [night], 山上 [on a mountain], and 合上 [to close]. When correct characters in these frames were replaced with their corresponding orthographic, homophonic, homovisemic, or unrelated mate, the resulting two-character pair never formed a semantically acceptable collocation. These character pairs were embedded as the final two characters in 100 different sentence frames, each of which was 7–14 characters in length ($M = 10$, $SD = 1.5$). Sentence contexts leading up to terminal characters were designed so that the final character would be highly predictable (following Liu et al., 2011, Ren et al., 2009). To test this, a cloze study was conducted with an independent sample of 20 university students from Hong Kong. They were asked to read each sentence up to, but not including, the final character and then guess what they thought the final character was most likely to be. The percentage of correct guesses per sentence frame ranged from 5%–100% and was high overall, with a mean of 75% ($SD = 30\%$) correct guesses. As only a limited number of characters were available that could fit into each character set, there were cases where designing a highly predictable sentence frame was not possible, leading to a small number of sentences with low-predictability terminal characters.

A within-items design was used such that sentence frames were identical across conditions, and only the final character differed according to condition. The final set of

stimuli consisted of five stimulus lists, each with the same 100 sentence frames. Within each list, 20 frames ended with correct characters, 20 with orthographic errors, 20 with homophonic errors, 20 with homovisemic errors, and 20 with unrelated errors. Across all lists, each sentence frame appeared one time in one of the five conditions, but lists were counterbalanced such that no participant was exposed to the same sentence frame or target character more than once. Table 5.2 shows an example sentence frame in each of the five different conditions. As this study included some readers with low reading proficiency, and thus more likely to experience reading fatigue, filler sentences were not used as to limit the experiment’s length.

Condition	Sentence
Correct character 晚上 /zi6 jin4/ [night]	她在那裡睡了三個 <u>晚上</u> 。 “She slept there for three <u>nights</u> .”
Orthographic error 晚止 /maan5/ + /zi2/ [night] + [stop]	她在那裡睡了三個 <u>晚止</u> 。
Homophonic error 晚尚 /maan5/ + /soeng6/ [night] + [esteem]	她在那裡睡了三個 <u>晚尚</u> 。
Homovisemic error 晚丈 /maan5/ + /zoeng6/ [night] + [husband]	她在那裡睡了三個 <u>晚丈</u> 。
Unrelated error 晚以 /maan5/ + /ji5/ [night] + [with]	她在那裡睡了三個 <u>晚以</u> 。

Table 5.2: *Set of example sentences from Experiment 1 in five conditions.* A set of example sentences used across the five item lists in Experiment 1. Target words are underlined for clarity.

Procedure

Sentences were presented to participants word-by-word. Each word appeared at the center of the screen for 500 ms, and a blank screen appeared for 100 ms after each word. Before each trial, a waiting signal ($\sim***\sim$) was visible in the center of the screen, remaining there until participants pressed a designated button to initiate the next trial. Participants were instructed to read each sentence silently and try to understand its meaning regardless of any character errors they might encounter. The order of item presentation was randomized for each participant. Simple yes-no comprehension questions were presented after approximately one-fifth of the sentences. Both hearing and deaf groups were able to answer with a relatively high degree of accuracy (hearing average score: $M = 97\%$, $SD = 4\%$; deaf average score: $M = 91\%$, $SD = 7\%$). In each group, half of the participants took part in Experiment 1 before Experiment 2, while the other half took part in Experiment 2 before Experiment 1.

Electroencephalography

Electroencephalograms (EEGs) were recorded at a 250 Hz sampling rate using a 129-channel HydroCel Geodesic Sensor Net from Electrical Geodesics Incorporated (EGI). Electrode impedances were kept below 50 k Ω , following the manufacturer's recommendation. The Cz electrode was used as the online reference, and average re-referencing was performed offline. Data was processed using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes in the MATLAB environment (The Mathworks, Inc.). The PREP preprocessing pipeline (Bigdely-Shamlo et al., 2015) was used to remove and interpolate bad channels automatically, and a high-pass IIR Butterworth filter of 0.1 Hz was applied to the continuous data. Data was epoched offline from -100 ms before to 500 ms after the onset of the target stimulus (i.e., the terminal word of each sentence). Average baseline correction was performed using the -100 ms pre-stimulus window. A 30 Hz low-pass filter was applied before plot generation, only after measuring mean amplitudes (Luck, 2014). Any epochs exceeding 100 μ V were discarded

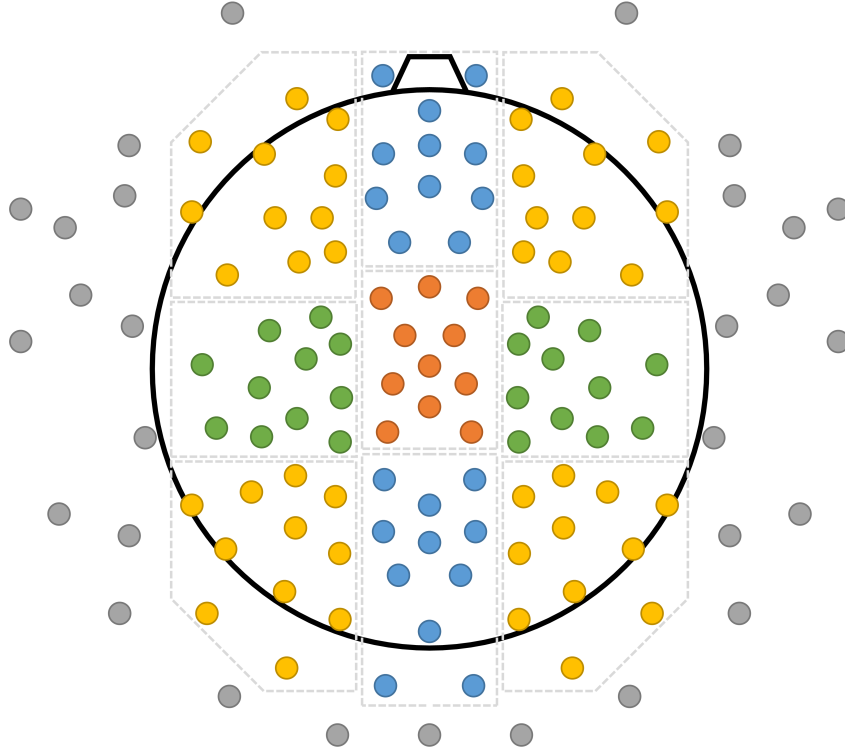


Figure 5.1: *ROIs for statistical analysis.*

from analysis (rejected trials across conditions, hearing data: $M = 7\%$, $SD = 1\%$; deaf data: $M = 8\%$, $SD = 1\%$).

ERP Analysis

Two time windows and nine electrode regions were selected for statistical analysis. The first time window of 150–300 ms covered the P200 component, and the second time window of 300–500 ms covered the N400 component. Regions of interest (ROIs; Figure 5.1) used for statistical analysis were left anterior (electrodes 25, 22, 32, 26, 23, 34, 33, 27, 24, 28, 20), mid anterior (21, 14, 15, 16, 18, 10, 19, 11, 4, 12, 5), right anterior (9, 8, 3, 2, 1, 124, 123, 122, 118, 117, 116), left central (29, 35, 30, 40, 36, 41, 46, 42, 37, 47, 53), mid central (13, 6, 112, 7, 106, 31, 129, 80, 55, 54, 79), right central (111, 105, 110, 104, 103, 109, 87, 93, 86, 98, 102), left posterior (50, 51, 52, 58, 59, 60, 64, 65, 66, 69, 70), mid posterior (61, 78, 62, 67, 77, 72, 71, 76, 75, 74, 82), and right posterior (92, 85, 97, 101, 91, 84, 96, 85, 90, 95, 89).

A repeated-measures analysis of variance (ANOVA) was conducted on mean amplitudes for each component with condition and region as within-subjects variables. Greenhouse-Geisser corrections were applied when the sphericity assumption was not satisfied. To assess the effects of each condition, significant interactions were followed with post-hoc tests comparing each experimental condition with the unrelated condition, which served as the control. Significance levels for multiple comparisons were adjusted using false discovery rate corrections, which is a technique that has been shown to perform well with ERP data (Causeur et al., 2012). For conciseness, the effects of region are only reported when found to interact with the experimental condition.

5.2.2 Results

Hearing participants

In the P200 window, there was significant interaction between condition and region [$F(32, 736) = 1.75, p < .05$]. Further tests revealed a significant effect of the correct condition at the mid anterior site ($p < .05$). Orthographic effects in the P200 were significant at the right anterior and mid anterior sites ($ps < .05$), and homophonic effects were significant at the right anterior ($p < .01$) and across the midline electrode sites ($ps < .05$). In the N400 window, the overall effect of condition was significant [$F(4, 92) = 11.80, p < .001$], as was the interaction between condition and region [$F(32, 736) = 2.17, p < .001$]. Tests revealed a significant effect of the correct condition across all electrodes. This effect was strongest in the mid central ($p < .01$), as well as left central and posterior sites ($p < .05$). There were no significant orthographic or phonological effects in the N400 window. Experiment 1 waveform plots and scalp maps for the hearing participants are shown in Figures 5.2a and 5.2b, respectively.

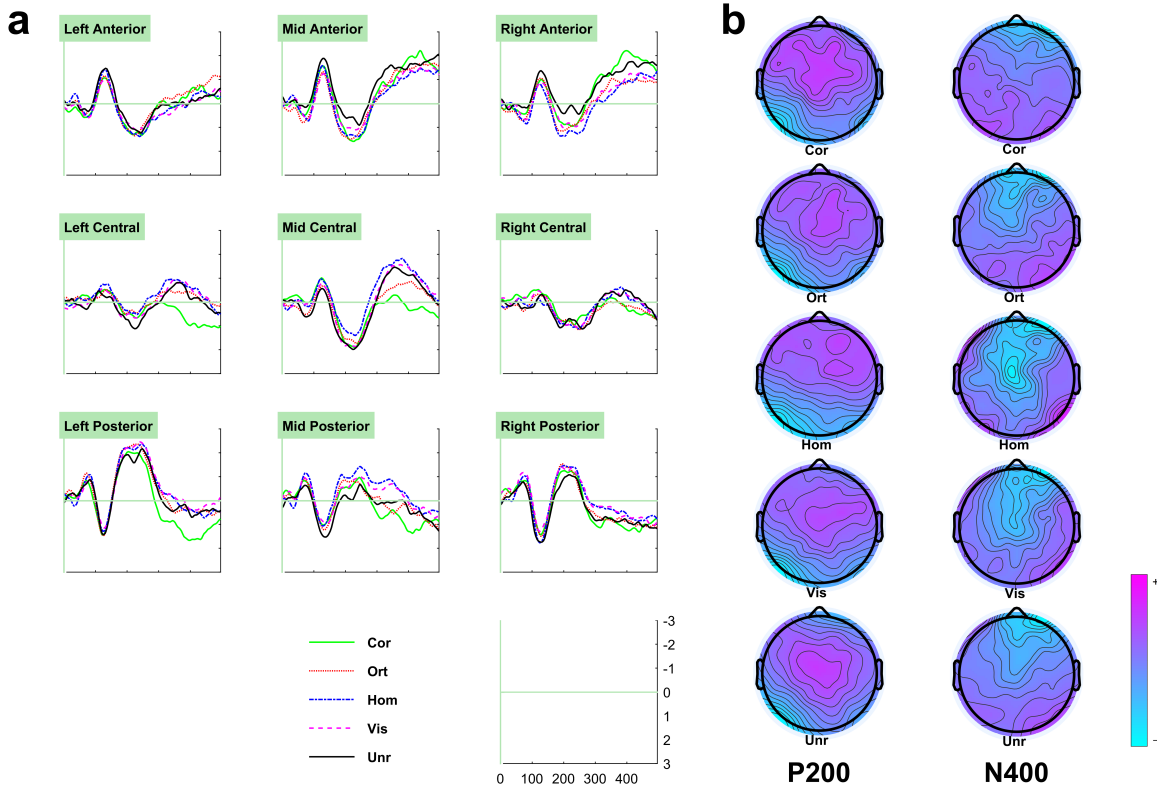


Figure 5.2: *Waveform plots and scalp maps for hearing participants in Experiment 1.*

Deaf participants

The effect of condition in the P200 window was not significant [$F(4, 92) = 1.56, p > .1$], nor was the interaction between condition and region [$F(32, 736) = 0.98, p > .1$]. In the N400 window, there was a significant effect of condition [$F(4, 92) = 13.90, p < .001$] and a significant interaction between condition and region [$F(32, 736) = 4.01, p < .001$]. Tests revealed that overall N400 amplitudes were significantly reduced in the correct ($p < .001$) and orthographic conditions ($p < .05$). For the correct condition, this effect was present in the mid central ($p < .001$), mid posterior ($p < .001$), left anterior ($p < .01$) and left posterior sites ($ps < .001$). The orthographic effect was present in the mid posterior electrodes ($p < .05$). There was also a significant effect of the homophonic condition, indicated by increased N400 amplitude, present in the right central electrodes ($p < .01$). Experiment 1 waveform plots and scalp maps for the deaf participants are presented in Figures 5.3a and 5.3b.

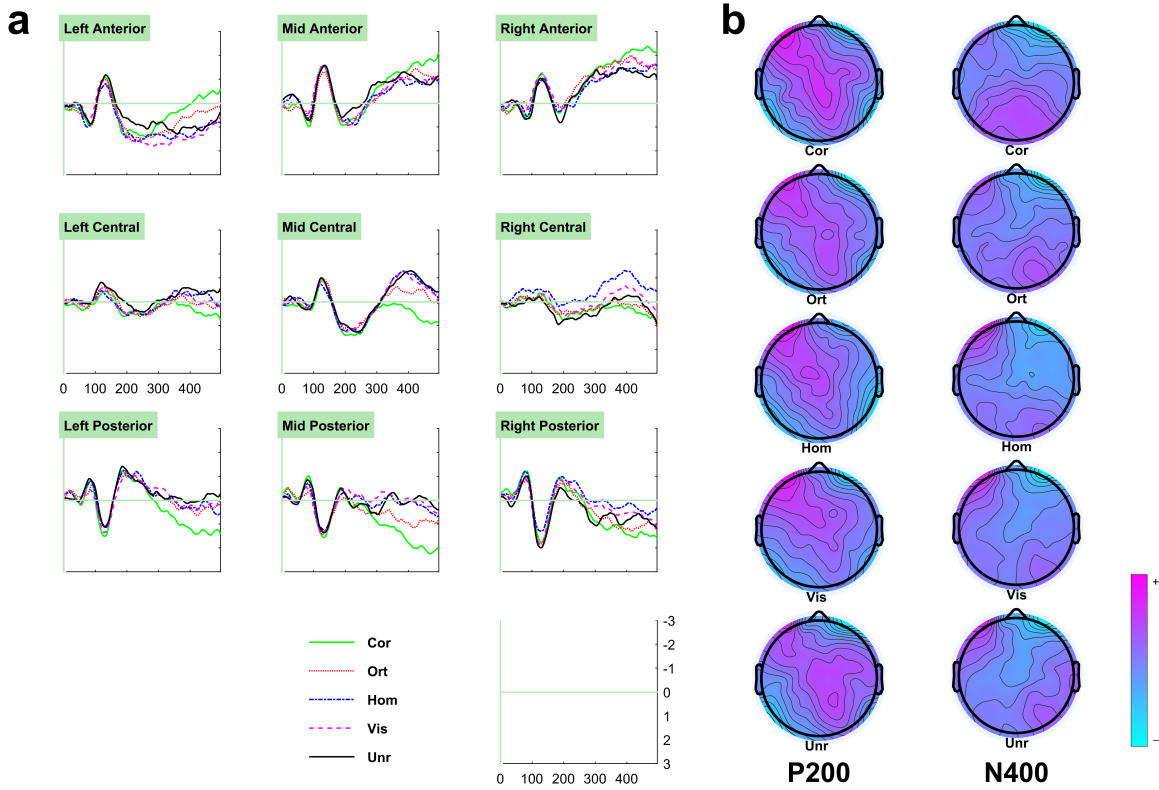


Figure 5.3: *Waveform plots and scalp maps for deaf participants in Experiment 1.*

5.3 Experiment 2

5.3.1 Method

Participants and background measures

The participants in Experiment 2 were the same as those in Experiment 1.

Materials

To construct the stimuli for Experiment 2, character pairs were selected that, based on their HKSL translations, overlapped in two or more sign phonological parameters (following Morford et al., 2011). For each target, a third character was selected that had a sign phonologically unrelated HKSL translation (also unrelated in orthography, Cantonese phonology, and meaning) to serve as the control. This selection process resulted in 68 sets of characters, each with a target character, a sign phonologically related character,

and an unrelated character.

To investigate, in an extended analysis, whether specific sign phonological parameters have different effects on processing (following Thierfelder, Wigglesworth, et al., 2020b), within the sign phonologically related condition, four sub-conditions were defined based on the specific parameters shared by the HKSL translation pairs. These sub-conditions included the following: HLM pairs (see example in Figure 5.4a), which overlapped in handshape, location, and movement ($n = 18$); HL pairs (Figure 5.4b), which overlapped in handshape and location but differed in movement ($n = 15$); HM pairs (Figure 5.4c), which overlapped in handshape and movement but differed in location ($n = 17$); and LM pairs (Figure 5.4d), which overlapped in location and movement but differed in handshape ($n = 18$).

To ensure that character pairs were not orthographically related, pairs that had overlapping semantic or phonetic radicals were avoided.³ No two characters in any pair had the same Cantonese pronunciation, and there was no interaction between HowNet (Dong et al., 2006) semantic similarity estimates and condition [$F(4, 99) = 1.98, p > .1$]. Mean character frequencies and stroke counts did not vary significantly across conditions [Frequency: $F(5, 207) = 0.45, p > .1$; strokes: $F(5, 207) = 1.01, p > .1$].

To verify that participants perceived a sign phonological relationship between the HKSL translations of target characters and their mates, a sign phonological relatedness study was carried out with the same group of deaf participants around two months after they had participated in the experiment. Participants were presented with each Chinese character pair used in the stimuli and asked to make a subjective judgment regarding how similar the HKSL translations of each pair were in terms of their sign phonology. Judgments were given on a scale of one (completely dissimilar in HKSL phonology) to five (highly similar in HKSL phonology). As most deaf participants were unfamiliar with judgment tasks of this sort, the questionnaire was administered by a deaf linguist who

³In the final set, due to the limited number of sign phonologically related pairs that could be found for each set of configurational parameters, two pairs that shared the 𠂇 [person] radical but had dissimilar components on the right side were retained.

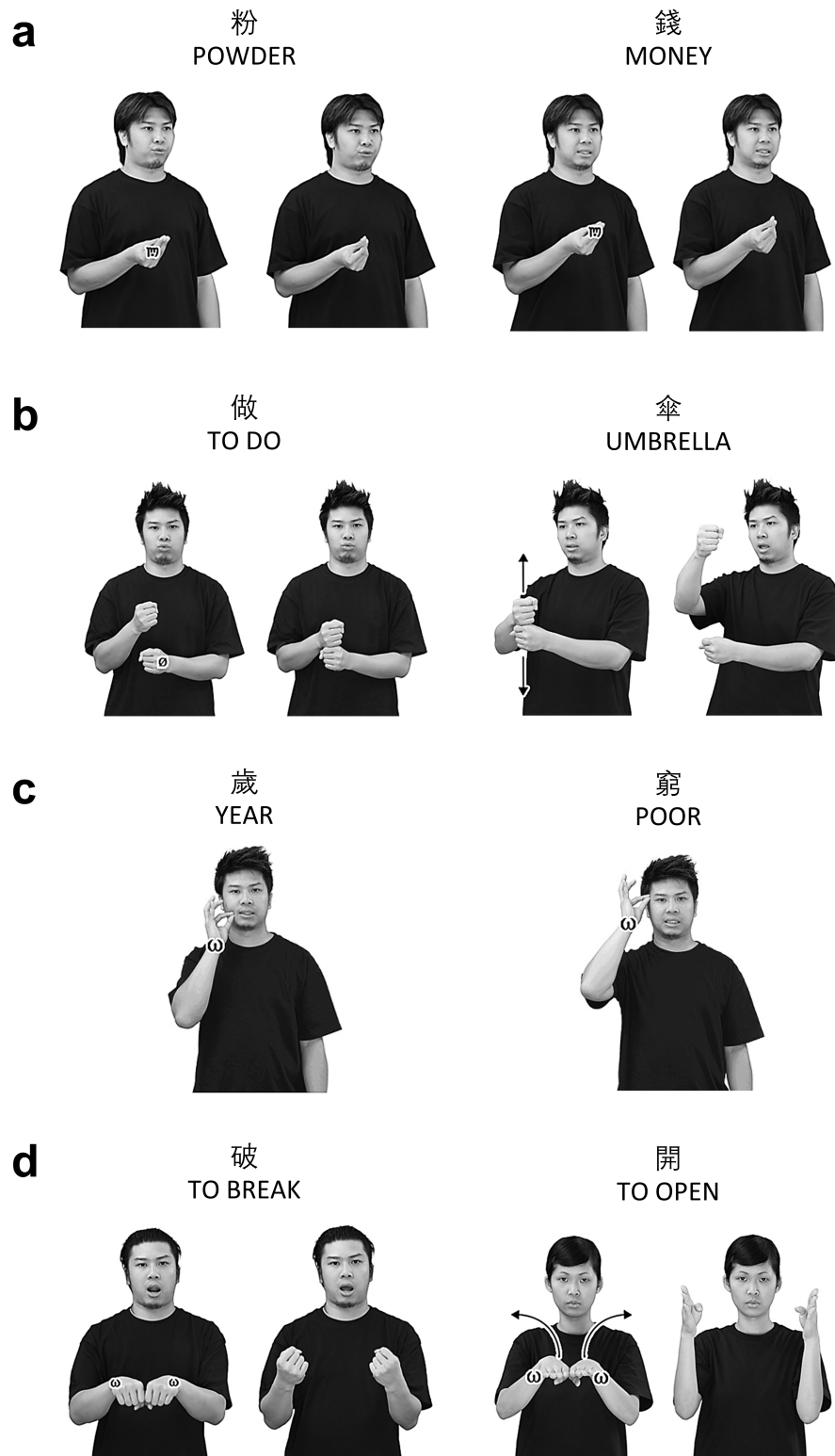


Figure 5.4: *Examples of sign phonologically related translation pairs.* Figure 5.4a shows an example of an HLM (handshape/location/movement) sign translation pair. Figure 5.4b shows an HL (handshape/location) sign translation pair. Figure 5.4c shows an HM (handshape/movement) sign translation pair. Figure 5.4d shows an LM (location/movement) sign translation pair. Images used with permission courtesy of the Asian SignBank (<http://cslds.org/asiansignbank/>).

was a native signer of HKSL. As expected, there was a significant interaction between sub-condition and HKSL phonological similarity [$F(4, 92) = 61.8, p < .001$]. HLM, HL, HM, and LM pairs were all rated as significantly more similar than unrelated pairs ($p < .001$). Of the related pairs, HLM pairs were rated as the most similar ($ps < .001$). HM pairs were rated as more similar than LM pairs ($p < .05$). HL pairs did not differ significantly from either HM pairs ($p > .1$) or LM pairs ($p > .05$). Character properties are summarized in Table 5.3.

	Identical Preview	Overall Sign Preview	HLM Sign Preview	HL Sign Preview	HM Sign Preview	LM Sign Preview	Unrelated Preview
Frequency	121 (112)	121 (110)	139 (114)	92 (81)	130 (118)	121 (127)	123 (117)
Semantic Relatedness	–	.20 (.10)	.35 (.34)	.18 (.30)	.17 (.10)	.11 (.09)	.26 (.25)
Sign Phonological Rating	–	2.4 (0.8)	3.5 (1.7)	2.0 (1.4)	2.1 (1.5)	1.8 (1.3)	1.1 (0.5)
Stroke Count	12.5 (5.3)	11.5 (5.3)	10.0 (5.3)	11.3 (3.6)	11.3 (4.7)	13.3 (6.7)	11.0 (4.3)

Table 5.3: *Experiment 2 character properties*. *SDs* in parentheses. Mean frequencies from Ho and Kwan (2001). Semantic similarity calculated using HowNet (Dong et al., 2006). Mean character properties of the sign phonologically related condition are divided by sub-condition in the HLM/HL/HM/LM columns and collapsed together in the Sign Phonologically Related column. H = handshape. L = location. M = movement.

Each target character was embedded as the second character in a two-character word (e.g., 枱 /caan1/ [table] was embedded into 餐枱 /caan1 toi4/ [dining-table]), which were each embedded into a unique sentence frame as the terminal word. Each target character was replaced with its sign phonologically related translation mate in the sign phonologically related condition (e.g., 餐安 /caan1/ [meal] + /ngon1/ [peace]) or an unrelated character in the control condition (e.g., 餐哥 /caan1/ [meal] + /go1/ [brother]). These character pairs never constituted a legal word in Standard Written Chinese or Cantonese.

As in Experiment 1, Experiment 2 used high-constraint sentence frames that were designed such that the terminal character was predictable, and this design was tested by conducting a cloze study with an independent sample of 20 Hong Kong university students. Overall predictability was the same as the sentence frames for Experiment 1. One sentence had no correct guesses, while the rest had 1–20 (5%–100%) per sentence,

with an overall average of 75% ($SD = 30\%$) correct guesses. Example sentences are shown in Table 5.4.

Due to the limited number of possible sign phonologically related translation pairs in HKSL, sentence frames could not be identical across the HLM, HL, HM, and LM sub-conditions. Therefore, sentences frames were designed to be highly similar across these sub-conditions according to a number of factors. The length of each sentence frame ranged from 7–14 characters ($M = 10$, $SD = 2$) and did not differ significantly between sub-conditions [$F(3, 64) = 0.17$, $p > .1$]. Cloze study results, as measured by the number of correct guesses, also did not differ significantly [$F(3, 64) = 1.19$, $p > .1$], suggesting that targets in the HLM, HL, HM, and LM sub-conditions were similarly predictable.

Condition	Sentence
Correct character 餐枱 /caan1 toi4/ [dining-table]	媽媽正忙著擺放 <u>餐枱</u> 。 “Mother is busy setting the dining-table.”
Sign phonological error 餐安 /caan1/ + /ngon1/ [meal] + [peace]	媽媽正忙著擺放 <u>餐枱</u> 。
Unrelated error 餐哥 /caan1/ + /go1/ [meal] + [brother]	媽媽正忙著擺放 <u>餐枱</u> 。

Table 5.4: *Set of example sentences from Experiment 2 in three conditions.* A set of example sentences used across the three lists in Experiment 2. Target words in this example are underlined for clarity. The sign phonologically related error in this example belongs to the HLM sub-condition.

To ensure that sentence frames were similar across sub-conditions in terms of complexity, the Chinese Readability Index Explorer/CRIE (Sung et al., 2016) was used to calculate the number of “difficult words” (defined as words not on the CRIE’s list of commonly used Chinese words), the average frequency of content words, and average per-character stroke count for each sentence. No significant differences between conditions were found [difficult words per sentence: $F(3, 64) = 0.73$, $p > .1$; average word

frequency per sentence: $F(3, 64) = 0.65$, $p > .1$; average strokes per sentence: $F(3, 64) = 0.47$, $p > .1$].

The final set of stimuli for Experiment 2 consisted of three lists of 68 sentences, each with the correct, sign phonologically related, and unrelated conditions comprising around one-third of each list. During the experiment, no participant was exposed to the same sentence frame or target character more than once. The three main conditions and four sub-conditions were counterbalanced across participants.

Procedure

Experiment 2 followed the same procedure as Experiment 1. Comprehension questions were presented after about one-fourth of the sentences. Both hearing and deaf groups were able to answer most of the questions accurately (hearing average score: $M = 94\%$, $SD = 9\%$; deaf average score: $M = 85\%$, $SD = 8\%$).

Electroencephalography

Continuous EEG data for Experiment 2 was processed following the same procedure as Experiment 1. Epochs exceeding 100 μV were discarded, which resulted in the rejection of an average of 8% ($SD = 1\%$) of the hearing data and 10% ($SD = 2\%$) of the deaf data across all conditions.

ERP Analysis

ERP analysis followed the same procedure as Experiment 1. However, in the first set of models, all sign phonologically related items were treated as a single variable to look for an overall effect of sign phonological relatedness, as this methodology is more comparable to what previous studies have done (Meade et al., 2017; Morford et al., 2011). In an extended analysis, an additional set of models was built to examine the individual effects of HLM, HL, HM, and LM sign phonological sub-conditions.

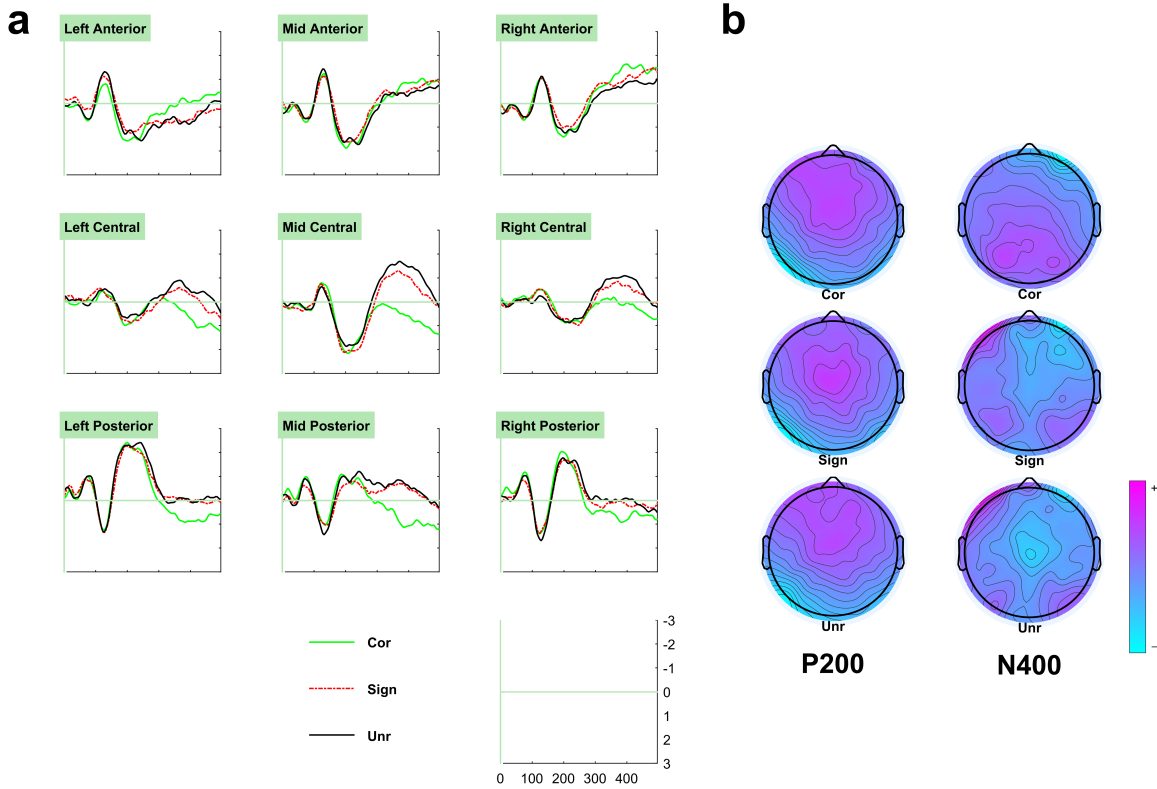


Figure 5.5: *Waveform plots and scalp maps for hearing participants in Experiment 2.*

5.3.2 Results

Hearing participants

In the P200 window, the overall effect of condition was not significant [$F(2, 46) = 1.52$, $p > .1$], nor did condition interact significantly with region [$F(16, 368) = 0.55$, $p > .1$]. In the N400 window, the effect of condition was significant [$F(2, 46) = 1.52$, $p < .001$] as was the interaction between condition and region [$F(16, 368) = 0.55$, $p < .01$]. Further tests revealed that N400 amplitudes were significantly reduced in the correct condition across electrodes ($p < .001$). These effects were strongest in the right central ($p < .01$), mid central ($p < .001$), mid posterior ($p < .001$), left central ($p < .01$) and left posterior electrode sites ($p < .05$). As expected, there were no effects of the sign phonological condition in any region ($ps > .1$). Experiment 2 waveform plots and scalp maps for the hearing participants are shown in Figures 5.5a/5.5b.

Deaf participants

In the P200 window, the overall effect of condition was not significant [$F(2, 46) = 0.48$, $p > .1$], but there was a significant interaction between condition and region [$F(16, 368) = 2.36$, $p < .05$]. Further tests revealed that the effect of the sign phonological condition was significant in the left anterior electrodes ($p < .05$) and approached significance in the mid posterior electrodes ($p = .08$). The effect of the correct condition was near-significant in the right anterior electrodes ($p = .07$). In the N400 window, the effect of condition and the interaction between condition and region were both significant [condition: $F(2, 46) = 17.03$, $p < .001$; condition $\times$ region: $F(16, 368) = 2.94$, $p < .05$]. Pairwise tests revealed that the N400 wave was significantly less negative in the correct condition than in the control condition ($p < .001$). This effect was present in the right central ($p < .01$), mid central ($p < .001$), mid posterior ($p < .05$), left anterior ($p < .01$), and left central ($p < .05$) electrode sites. There was no effect of the sign phonological condition in the N400 window ($ps > .1$). In the extended analysis, the difference between unrelated controls and the HM condition was significant in the mid central electrodes ($p < .05$) in the P200 window and near-significant for the LM condition in the left anterior electrodes ($p = .06$). Experiment 2 waveform plots and scalp maps for the deaf participants are shown in Figures 5.6a/5.6b.

5.4 Discussion

The goal of this study was to examine the patterns of Cantonese and HKSL phonological activation among Hong Kong deaf readers using the ERP technique. To do this, two experiments using the error disruption paradigm were carried out while recording participants' EEGs. Experiment 1 focused on orthographic and spoken phonological processing and included correct, orthographic, homophonic, homovisemic and unrelated conditions. Experiment 2 focused on sign phonological processing and included correct, sign phonological (with four sub-conditions: HLM, HL, HM, and LM), and unrelated conditions.

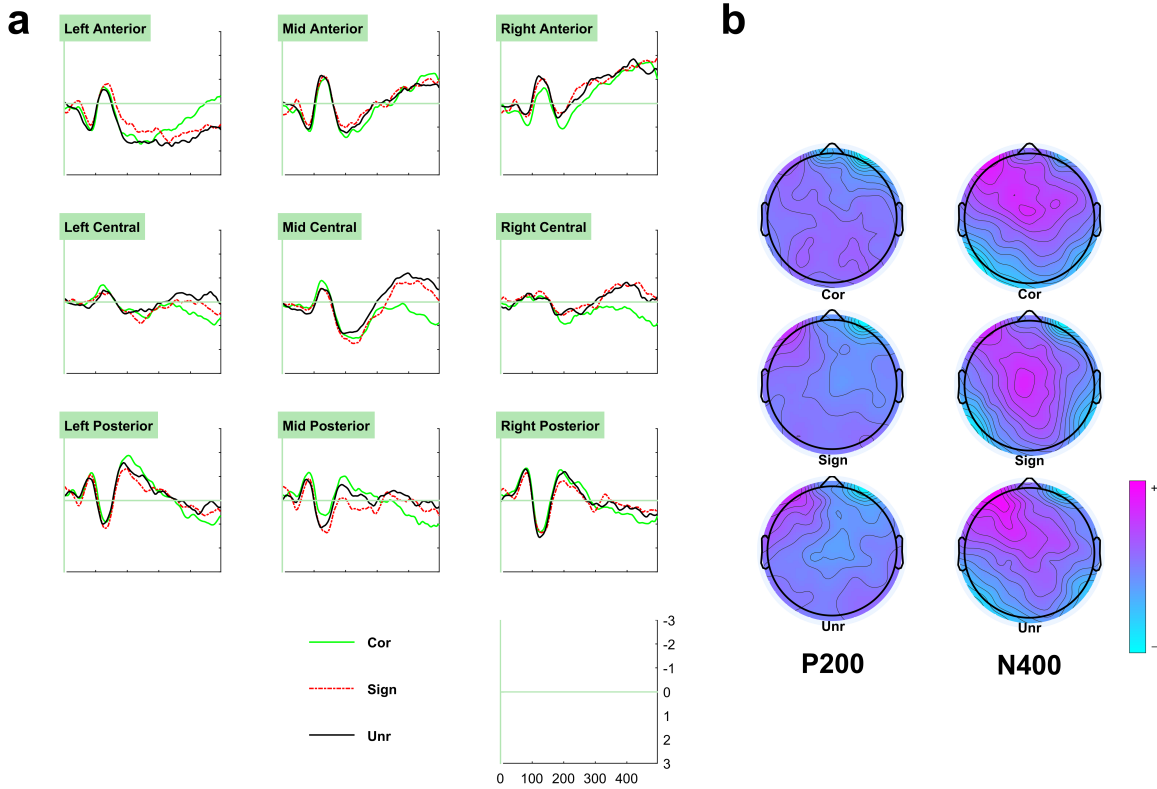


Figure 5.6: *Waveform plots and scalp maps for deaf participants in Experiment 2.*

Two time-windows were examined to cover the P200 (150–300 ms) and N400 (300–500 ms) components. Significant differences in mean wave amplitudes between the unrelated condition and orthographically or sign/spoken phonologically related conditions were taken as evidence of orthographic and sign/spoken phonological activation, respectively.

5.4.1 Hearing readers—Experiments 1 & 2

Both experiments were conducted with an unmatched group of hearing readers to see how skilled readers respond to the experimental stimuli. In Experiment 1, orthographic and homophonic effects, reflected by increased wave amplitudes, emerged early in the P200, which supports the conclusions of prior studies that the P200 can be modulated by phonological (Kong et al., 2010; Liu et al., 2011; Zhang et al., 2009) and orthographic (Kong et al., 2012) information in Chinese reading. In contrast to Ren et al. (2009), there was no significant effect of phonology among hearing readers in the N400. In

Experiment 2, as expected, there was no effect of the sign phonological condition in either the P200 or N400 window. This suggests that the Experiment 2 stimuli were unlikely to elicit any unintended orthographic, phonological, or semantic effects, and thus, any sign phonological effects found among deaf readers can most likely be attributed to the influence of HKSL.

5.4.2 Deaf readers—Experiment 1

In Experiment 1, among the deaf readers, there were no orthographic or phonological effects in the P200 window, but N400 amplitudes were significantly reduced in the orthographic condition across all electrodes. While this was not in line with the hypothesis that an orthographic effect would emerge earlier in the P200, the finding of a strong facilitative effect of orthography is in line with past research that has shown that deaf readers tend to activate word meanings directly through orthographic representations (Bélanger et al., 2013; Thierfelder, Wigglesworth, et al., 2020a; M. Yan et al., 2015).

There was a significant effect of the homophonic condition in the right central electrodes, suggesting there is some degree of late Cantonese phonological activation among Hong Kong deaf readers. The fact that it emerged only in the N400 window aligns with the findings of P. Li et al. (2017), who found a late-emerging phonological effect among deaf readers of Chinese in the N400 (compared to hearing readers, for whom phonological effects emerged in the N200 and P200 components). In the present study, N400 amplitudes were increased, rather than reduced, suggesting a possible phonological interference effect. While not typical, a similar pattern of phonological interference was observed among deaf signers in Gutiérrez et al. (2012)—in their study, however, the interference resulted from sign phonology. The findings of Experiment 1 offer support for some of the conclusions of Thierfelder, Wigglesworth, et al. (2020a), who found that deaf readers mainly relied on orthography, but did activate phonological representations when target words were in high constraint sentence contexts. There were no significant effects associated with the homovisemic condition, so it does not appear that deaf readers

were activating visemic representations within the first 500 ms of processing (see further discussion below).

5.4.3 Deaf readers—Experiment 2

In Experiment 2, P200 amplitudes were significantly reduced in the sign phonological condition, which indicates that sign phonology can modulate the P200 component in deaf readers, just as spoken phonology can in hearing readers. The P200 sign phonological effect was significant at the left anterior ROI, which is a region sensitive to lexical competition (Carreiras et al., 2006). The decreased P200 (which may indicate interference rather than facilitation—see Kong et al., 2010) in this region seems to suggest that sign phonologically related errors lead to competition between the lexical representation activated top-down from the high-constraint sentence context and the lexical representation activated bottom-up from through orthography. This is in line with the sign phonological interference effects found in prior studies (Morford et al., 2019; Morford et al., 2011; Pan et al., 2015; Thierfelder, Wigglesworth, et al., 2020b).

The extended analysis for Experiment 2 examined whether differences in overlapping sign phonological parameters led to different patterns of activation. It was found that significant effects were mainly associated with the HM condition, while the effect of the LM condition approached significance. No significant effects were associated with the HLM and HL conditions. However, the finding that P200 effects were strongest in the HM sub-condition is interesting as it aligns with the findings of Thierfelder, Wigglesworth, et al.’s (2020b) eye-tracking study. In their study, interference effects associated with the HM condition emerged earlier than the other sign phonologically related conditions, while the HLM condition produced slightly later interference effects. They concluded that handshape and movement led to stronger competition between the lexical representations overlapping on these parameters, resulting in a high degree of processing interference.

It is unclear why there was no early effect of the HLM sub-condition, given the apparent importance of the handshape and movement parameters in sign activation processes.

However, if deaf readers are relying heavily on sign phonology in early processing, it is possible that readers are not initially detecting a mismatch at all as the target phonological representation (activated top-down by the high-constraint sentence) is a complete match with the phonological representation associated with the terminal character. This explanation would also account for why Thierfelder, Wigglesworth, et al. (2020b) found that sign phonological interference effects emerged later in the HLM sub-condition than in the HM sub-condition. While these patterns are interesting, the findings of this extended analysis should be regarded as tentative given the limited number of observations each sub-condition (due to the limited number of matching pairs available in HKSL).

5.4.4 Theoretical implications

According to the lexical constituency model (C. A. Perfetti et al., 2005), a word's identity is specified by three interconnected constituents: orthographic, phonological, and semantic. When someone reads a word, its orthographic representation is retrieved from memory, and the activation of its phonological and semantic components automatically proceed from there. From the results, in line with this model, it was found that ERP components in deaf readers can be independently modulated by Chinese orthography, as well as Cantonese and HKSL phonology. For the university-level hearing readers, phonological information was found to modulate the P200 in high-constraint sentences. For deaf readers, there was a similar modulatory effect based on sign phonology rather than spoken phonology (while the effects of spoken phonology emerged only later). Thus, the findings suggest that lexical representations in bimodal bilingual deaf readers have both spoken and sign phonological constituents. Being sign dominant, however, sign phonology for deaf readers can play an early role in lexical access, analogous to the role of spoken phonology in hearing readers.

These findings also have implications specifically for models of deaf reading. The dual-route cascaded model of reading by deaf adults (Elliott et al., 2012) posited that phonological units in deaf readers' lexicons are based on visemes acquired through lipread-

ing rather than sounds associated with spoken phonology. Thierfelder, Wigglesworth, et al. (2020a) found some evidence that deaf readers use visemes, but this was primarily in late processing—during re-reading as an error recovery strategy. However, they did find some evidence that deaf readers with lower reading fluency might use visemes in early processing when contextual predictability was high. In line with the dual-route cascaded model of reading by deaf adults (Elliott et al., 2012) and the more general dual-route model on which it was based, the data did suggest that deaf readers can access meaning via both orthographic and phonological routes. However, the results could not verify that deaf readers’ Cantonese phonological representations were based on visemic representations as there was no significant effect of the homovisemic condition. A post-hoc check was carried out to look for correlations between mean amplitudes in the homovisemic condition and reading test scores but found none ($ps > .1$). Therefore, if Hong Kong deaf readers do use visemes, this is more likely to be a feature of late processing.

Thierfelder, Wigglesworth, et al. (2020a) suggested that, like hearing readers of Chinese, deaf bimodal bilingual readers of Chinese can access meaning directly via orthography or indirectly via phonology. However, deaf readers have access to multiple phonological representations for each word (e.g., visual-tactile or sound-based representations, visemic representations, and sign-based representations), and which phonological representation is activated at any given time is contingent on context- and reader-dependent factors. Based on the findings of both experiments, more specific predictions about the time course of spoken and sign phonological activation can be made.

The results of these experiments suggest that Hong Kong deaf readers of Chinese activate HKSL phonology in early word processing. While there was evidence that they can activate Cantonese-based phonological representations, this effect emerged later in the N400 window. Evidence of phonological activation in early processing is generally taken as indicating phonological involvement in the activation of word meanings. In contrast, when phonological activation occurs later, it is assumed to serving an integrative function (Leinenger, 2014), such as binding word meanings together in their sentential

context. Taken together, the results of this study provide converging evidence with Thierfelder, Wigglesworth, et al. (2020b) and Thierfelder, Wigglesworth, et al. (2020a) that sign phonological activation occurs very early in deaf readers, while spoken phonological activation emerges slightly later. Thus, deaf readers may rely more on sign phonology for initially accessing word meanings, while spoken phonology might play a role in integrating those word meanings into context and guiding parsing processes (like the proposed role of spoken phonology in hearing readers—see Clifton, 2015). While more research is needed on this topic, it would be interesting to investigate this further as it would suggest that both types of phonological code play important, though different, roles in deaf reading.

5.5 Limitations

There were three main limitations of this study that should be noted. The first issue was related to item design. As some of the readers in the deaf group were relatively low in reading proficiency and more likely to experience some degree of reading fatigue during long reading experiments, the length of the two experiments was kept as short as possible. Therefore, stimuli did not include filler items to distract participants from the error patterns in the experiments. It is possible that some of the effects found in this study were stronger than they would have been if the different error types were less noticeable. Second, due to practical limitations at the time of the study, the two experiments did not include a well-matched hearing comparison group. Doing so would have been advantageous as it would have allowed for a direct comparison the two groups and provide a better picture of how reading processes in deaf and hearing readers differ. Finally, due to the limited number of available HKSL phonologically related character pairs in each of the sub-conditions (HLM, HL, HM, and LM), one cannot draw very strong conclusions from the extended analysis. Some sign languages may have a higher number of phonologically similar signs that could be used for studies similar to the current one,

so further research in other deaf communities would be highly valuable for understanding the roles of different sign phonological parameters in lexical access.

5.6 Conclusion

The primary focus of this study was to investigate the time course of spoken and sign phonological activation in deaf readers. The results of the two experiments suggest that when reading high-constraint sentences, sign phonological representations are activated early in the P200 window, while spoken phonological representations are activated later in the N400 window. These findings might suggest that for deaf readers, sign and spoken phonological representations are involved in different aspects of reading processing—sign phonological activation may be more involved in the early activation of word meanings, while spoken phonological activation may be more involved in integrative processes. In sum, bimodal bilingual deaf readers can activate both sign and spoken code during reading, and both kinds of code are important in that they each appear to play a unique role in facilitating reading comprehension.

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Chapter 6

Discussion and conclusion

6.1 Discussion

This thesis aimed to build an in-depth picture of orthographic, spoken phonological, and sign phonological processing in Hong Kong deaf readers. Chapter 1 gave a broad overview of the research on deaf literacy and literacy development in English and Chinese while also providing background on the Hong Kong deaf community, and why reading research is needed for this under-studied group. Furthermore, this chapter explained why eye fixations and ERPs were used in our methodological approach for investigating reading processing and gave an overview of the research questions addressed in the main chapters of the thesis. Following this, Chapters 2–5 each focused on a different study that was carried out to address research questions related to the aim of the thesis.

The research questions (RQs) addressed by each chapter that relate to the overall research goal can be summarized as follows:

Chapter 2: (RQ1) What is the time course of orthographic and phonological activation in Cantonese-speaking readers of Chinese? (RQ2) Can phonological activation in Chinese reading be modulated by contextual predictability?

Chapter 3: (RQ3) What is the time course of orthographic and phonological activation in Hong Kong deaf readers? (RQ4) How are orthographic and phonological

processing modulated by contextual predictability and reading level? (RQ5) What is the nature of phonological units in deaf readers' mental lexicons?

Chapter 4: (RQ6) Do Hong Kong deaf readers activate HKSL representations during reading? (RQ7) How do the different HKSL phonological parameters of handshape, location, and movement affect reading processing?

Chapter 5: (RQ8) Is there evidence of orthographic and sign/spoken phonological modulation of ERP components in Hong Kong deaf readers? (RQ9) What is the relative time course of spoken and sign phonological activation? (RQ10) Does evidence from ERPs converge with the eye-tracking data of the previous studies?

This final chapter summarizes the studies discussed in Chapters 2–5, addressing the ten RQs, and discuss how each has contributed to the overall research goal. Finally, this chapter concludes with a discussion of the theoretical and practical implications of the research findings, as well as methodological issues and directions for future research. To keep the discussion concise, this chapter does not address findings related to the hearing comparison groups involved in the studies for Chapters 3–5.

6.1.1 Chapter 2

Chapter 2 reported on the pilot eye-tracking study, *The effect of word predictability on phonological activation in Cantonese reading: A study of eye fixations and pupillary response*. This chapter was the only chapter of this thesis to focus solely on hearing readers. The intention of this study was to investigate the time course of orthographic and phonological activation, while also investigating the role of contextual predictability, during Chinese sentence reading in hearing Cantonese-speaking readers from Hong Kong. To do this, an error disruption paradigm was used, which included correct, orthographic, homophonic, and unrelated conditions. Using an SMI RED-n Scientific eye-tracking device, participants' eye movements and pupil sizes were recorded as they read the stimulus sentences. The pattern of results found for each main condition was in line with previous eye-tracking studies on Chinese reading (Feng et al., 2001; Wong & Chen, 1999; Zhou

et al., 2018). Readers appeared to be accessing word meanings primarily through orthographic representations in early processing, which was reflected by the fact that their first fixation durations (FFDs) and gaze durations (GDs) were shorter on orthographic errors than on unrelated errors. In late processing, the evidence indicated that both orthographic and homophonic representations facilitated lexical access as total reading times (TRTs) were significantly shorter in the orthographic and homophonic conditions than in the unrelated condition.

However, the findings diverged somewhat from prior research on Chinese reading (specifically, Feng et al., 2001) in that it was found that high degrees of contextual predictability led to shorter fixation times on homophonic errors relative to controls. This finding indicated that readers were able to resolve homophonic errors (via phonological cues) more quickly when this process was facilitated top-down by high levels of contextual predictability. In the analysis of pupillary response, it was found that readers' pupil diameters increased significantly when reading words with orthographic errors (relative to correct characters as the baseline measurement), which suggested that resolving orthographic errors in Chinese requires the recruitment of increased cognitive resources.

To my knowledge, this study is the first to demonstrate that phonological processing in Chinese reading can be facilitated by top-down semantic integration processes, though multiple studies have found evidence of this in English reading (Daneman & Reingold, 2000; Feng et al., 2001; Rayner et al., 1998). This finding also lends support to some of the claims of the lexical constituency hypothesis (C. A. Perfetti et al., 2005)—namely, that phonological activation is universal across scripts and is important for processes down-stream from lexical access, such as integrating lexical items into syntax.

In addressing the aims of the thesis, this study was important for two reasons. First, it served to show that the design of the stimuli and experiment was sound and elicited orthographic and phonological processing effects in hearing readers similar to those expected based on prior research. This outcome suggested that the experiment could be extended to investigate these same processes in deaf readers. Furthermore, it showed

that high levels of contextual predictability could provide ideal conditions for facilitating phonological activation in Chinese reading. If deaf readers were not found to activate phonological representations even in these high predictability contexts, it would strongly suggest that deaf readers do not access word meanings through spoken phonological representations, in line with what some previous studies have suggested (Bélanger, Baum, et al., 2012; Bélanger et al., 2013).

In sum, this study showed that hearing Cantonese-speaking readers of Chinese activate word meanings primarily through orthographic representations in early processing, while both orthographic and phonological representations play a role in lexical access during late processing (RQ1). Findings addressing RQ2 suggested that phonological representations can be activated in early processing via semantics in high predictability contexts.

6.1.2 Chapter 3

Chapter 3 (*Orthographic and phonological processing in Hong Kong deaf readers: An eye-tracking study*) reported on a study focusing on deaf readers in Hong Kong. As with the pilot study reported on in Chapter 2, this study used an error disruption paradigm. The majority of sentence frames and target characters were borrowed from the first study. However, in addition to the correct, orthographic, homophonic, and unrelated conditions, also included was one additional condition, homovisemic, which was added so that the dual-route cascaded model of reading by deaf adults could be tested (Elliott et al., 2012) for Hong Kong deaf readers. As discussed in the introduction, and again in Chapter 3, the dual-route cascaded model of reading by deaf adults posits that deaf readers' phonological representations are based on visemes associated with a word's pronunciation and are therefore not sound-based as they are for hearing readers. As a single viseme might map to multiple possible phonological forms (for example, a single visemic form maps to both mom and bomb, as these words cannot be distinguished by mouth shape), the visemic forms available to deaf readers would be less detailed than the sound-based forms available to hearing readers.

As with the study in Chapter 2, predictability was included as a variable; however, an additional predictor, reading fluency level, was also included as some evidence has suggested that phonological activation might occur in higher fluency deaf readers, but not in those with lower fluency (M. Yan et al., 2015). The same dependent eye fixation time measurements (FFD, GD, and TRT) were used as the study in Chapter 2. However, because a different eye-tracker was used, an Eyelink 1000 Plus, which was not ideal for measuring pupillary response, pupil size measurements were not measured in the second study.

In the analysis of the main effects of each condition, it was found that in early processing (measured by FFD and GD), deaf readers accessed word meanings through orthographic representations. In the late measure of TRT, the results suggested that deaf readers were accessing word meanings through visemic representations when rereading for error recovery. When looking at the influence of predictability, however, it was apparent that most deaf readers could distinguish homophonic and homovisemic characters, as only homophonic and orthographic, but not homovisemic, characters facilitated word integration in high predictability contexts. Importantly, this finding suggests that, similar to hearing readers, deaf readers can also activate spoken phonological representations top-down via semantics.

In the analysis of the effects of reading fluency, deaf readers with higher levels of reading fluency could more quickly resolve homophonic and orthographic errors. Furthermore, they received more contextual facilitation from high predictability sentences during early processing and spent less time rereading, which seemed to indicate that they had stronger message-level processing abilities. Lower fluency deaf readers, however, were more facilitated by high levels of contextual predictability in GD when resolving both homophonic and homovisemic errors, which might indicate that they had a stronger tendency to use contextual information to facilitate their phonological activation processes. This pattern might also have been an indication that this subset of readers uses visemic rather than detailed sound-based or visual-tactile spoken phonological codes.

This chapter concluded by discussing some theoretical implications of the findings. Firstly, rather than being an issue more specifically related to phonological coding ability (see discussions in C. A. Perfetti & Sandak, 2000, and Y. Wang et al., 2008), lower reading fluency in deaf readers is due to having lexicons with lower quality lexical items. C. A. Perfetti and Hart (2002) proposed that skilled readers have high-quality lexical representations with well-defined component orthographic, phonological, and semantic representations. As lower fluency deaf readers in the study seemed to have weaker message-level processing skills, in addition to slower processing speeds when resolving errors based on phonological and orthographic cues, this study suggested that the reading difficulties they face are due to underdeveloped lexical representations with incomplete or poorly-defined orthographic, phonological, and semantic constituents. These low-quality lexical representations lead to weaknesses in multiple aspects of reading.

Addressing another theoretical aspect of deaf reading, the findings concerning the dual-route cascaded model of reading by deaf adults (Elliott et al., 2012) was also discussed, for which the results offered some limited support. The results of the study suggested that visemic representations seemed to be limited to late-stage error recovery, and possibly among lower fluency readers in high predictability contexts. While Elliott et al. (2012) suggested that some deaf readers use visemes instead of more detailed phonological forms, the data suggested that, with the possible exception of a subset of lower fluency deaf readers, deaf readers generally use character-viseme mapping as an error recovery strategy. This tendency was apparent because their homovisemic error recovery speeds increased over the course of the experiment, indicating that they used visemic code adaptively. From this, it seems that deaf readers are flexible with how they use phonological code during reading.

To capture reading processes among deaf readers of Chinese, an adjusted dual-route model of Chinese reading describes the process that unfolds when deaf readers recognize a Chinese character or word: (1) the Chinese character is fixated, and its visual features are detected; (2) the character's radical components are activated by their visual fea-

tures; (3) the orthographic lexicon activates representation(s) which contain the same radicals and configuration; (4) the corresponding sign phonological, visemic, or spoken phonological representation(s) is activated; (5) the semantic representation is activated, either directly from the orthographic representation or indirectly via an intermediary phonological representation.

Finally, the findings presented in Chapter 3 were summarized as they relate research questions. Regarding the time course of orthographic and phonological activation (RQ3), Hong Kong deaf readers activate word meanings through orthographic representations in early processing. In late processing, they activate word meanings through both orthographic and phonological representations. Contextual predictability was found to have a modulative effect, particularly in early processing, and allowed deaf readers to resolve both orthographic and homophonic errors more quickly (RQ4). While deaf readers were found to activate visemic representations in late processing, this appeared to be an error recovery strategy, and most deaf readers had access to detailed phonological representations, which might have been based on sound or visual-tactile information acquired through residual hearing or speech training (RQ5).

6.1.3 Chapter 4

In Chapter 4, *Sign Phonological Parameters Modulate Parafoveal Preview Effects in Deaf Readers*, the parafoveal preview study was presented which investigated sign phonological activation among Hong Kong deaf readers. While research on deaf signers of other communities has suggested that deaf signers unconsciously activate signed translations of written words (Chiu et al., 2016; Chiu & Wu, 2016; Kubus et al., 2015; Meade et al., 2017; Morford et al., 2019; Morford et al., 2011; Pan et al., 2015; Quandt & Kubicek, 2018), this has never been tested specifically in the Hong Kong deaf community. Beyond just looking at whether they activate phonology, however, interest was focused on whether different sign phonological parameters play different roles in activation processes. To do this, the parafoveal preview study included a correct condition, a sign phonologically

related condition, and an unrelated condition. Furthermore, within the sign phonologically related condition, there were four types of preview-target pair (which comprised the four sub-conditions): (1) HLM pairs, which had HKSL translations that overlapped in three parameters-handshape, location, and movement; (2) HL pairs, which overlapped in only handshape and location; (3) HM pairs, which only overlapped in handshape and movement; and (4) LM pairs, which only overlapped in location and movement.

The strongest effects were associated with the HM sub-condition, which emerged in FFD, earlier than the HLM, HL, and LM sub-conditions. HLM and HL effects emerged slightly later in GD, and LM effects emerged last, in total reading time. Based on the fact that significant effects associated with the LM condition emerged latest, the study concluded that eliciting early sign phonological activation effects required that preview-target pairs overlap in handshape. Furthermore, HM and HLM were associated with preview cost, while the other two sub-conditions were associated with preview benefit. Preview cost is believed to be a result of high degrees of competition between the meanings activated by the preview and target words (Pan et al., 2016; Pan et al., 2015; M. Yan et al., 2015). The finding of preview cost associated with preview-target pairs that overlapped in both handshape and movement (both HM and HLM sub-conditions) suggested that these parameters led to the strongest activation of both the preview and correct target, resulting in competition between the activated meanings. This is likely to be an indication that these parameters are of special importance in lexical access during reading. The other parametric configurations, HL and LM, led to preview benefit, suggesting that when previews and targets overlapped in location plus one other parameter (handshape or movement), the correct target was activated by the phonological features it shared with HL/LM previews. The degree of activation, however, was just enough to facilitate processing of the correct target once directly fixated without creating interference between the activated representations.

An extended analysis also looked at the effects of age of HKSL acquisition, with findings suggesting that deaf readers who learned HKSL later benefitted less from identical

previews and were less interrupted by unrelated previews, which seems to suggest that their parafoveal processing was not as strong as deaf readers who learned sign language earlier. This is interesting as several studies on deaf signers have shown them to have an enhanced perceptual span (Bélanger et al., 2018; Bélanger, Slattery, et al., 2012; M. Yan et al., 2015), which allows for more efficient parafoveal processing. The pattern seems to indicate that signers who acquired HKSL later in life might not have this enhanced visual span.

In summary, the study presented in Chapter 4 showed evidence that Hong Kong deaf readers activate sign phonological representations associated with the Chinese words (RQ6) and that this activation influences both early and late stages of processing. Regarding RQ7, the pattern of results suggested that handshape is of special importance in facilitating early processing effects. Furthermore, effects were strongest when previews and targets overlapped in both handshape and movement, which might indicate that these two parameters in combination most strongly activate sign phonologically related lexical representations.

6.1.4 Chapter 5

In Chapter 5, *The time course of Cantonese and Hong Kong Sign Language phonological activation: An ERP study of deaf bimodal bilingual readers of Chinese*, reported on an error disruption study with ERPs, in which electroencephalogram recordings were used to measure brain wave response as participants read sentences containing terminal character errors. The aim of the two experiments used in this study was to investigate the time course of spoken phonological and sign phonological activation and to look for converging evidence to support the findings from Chapters 3 and 4.

Both Experiment 1 and Experiment 2 used high-constraint sentences in which the target character (always the last character of the sentence) was predictable. Experiment 1, like the error disruption study with eye-tracking (Chapter 3), had five main conditions: correct, orthographic, homophonic, homovisemic, and unrelated. Experiment 2, whose

design reflected the parafoveal preview study (Chapter 4), had three conditions: correct, sign phonologically related, and unrelated. Within the sign phonologically related condition, there were four sub-conditions (also following the parafoveal preview study): HLM, HM, HL, and LM.

In Experiment 1, there was evidence that deaf readers activated orthographic and phonological representations in the N400 window. Orthographic activation was particularly strong, showing statistical significance across all electrodes, and appeared to facilitate lexical access processes (evidenced by the fact that amplitudes were less negative than in the unrelated condition). This finding offered support for the overarching conclusions of the first error disruption study conducted with deaf readers (Chapter 3)—namely, that deaf readers mainly access word meanings through orthography and that phonological activation can occur in early processing when facilitated by context. However, there was no converging evidence to support the claim that deaf readers use visemes. This might have been because the ERP study focused on early processing only, and visemic effects were found to be mainly confined to late processing during rereading in the eye-tracking study.

In Experiment 2, there was evidence that deaf readers activated sign phonological representations in the P200 window. The further, extended analysis suggested that these significant effects were strongly associated with the HM condition. These findings lent support to those reported in Chapter 4. That is, Hong Kong deaf readers activate sign phonological representations in early processing when reading sentences, and that the handshape and movement parameters appear to be particularly important in accessing word meanings.

Taken together, Experiments 1 and 2 suggested that deaf readers activate sign phonological representations in early processing and that spoken phonological activation occurs slightly later, a pattern that has been reflected in studies of sign phonological (Chiu & Wu, 2016; Pan et al., 2015; Thierfelder, Wigglesworth, et al., 2020b) and spoken phonological (Thierfelder, Wigglesworth, et al., 2020a; M. Yan et al., 2015) activation in

Chinese reading. It was proposed that this finding might suggest that deaf readers use the two types of phonological code in different ways. They use sign phonological code for quickly accessing word meanings, and then use spoken phonological code for integrating those word meanings into the sentence.

In the ERP study described in Chapter 5, there was evidence that orthography, spoken phonology, and sign phonology can independently modulate ERP components in Hong Kong deaf readers (RQ8). Specifically, sign phonological effects emerged in the P200 component, while orthographic and spoken phonological effects emerged in the N400. Taken together, these findings suggest that deaf readers activate sign phonological representations in early processing and activate spoken phonological representations in late processing (RQ9). Regarding RQ10, this ERP study provided converging evidence for some, but not all, findings of the earlier eye-tracking studies. First, the early emergence of sign phonological effects and later emergence of spoken phonological effects, as well as the fact that orthographic effects were found to be strongest (i.e., significant across all electrodes), does support the overall pattern in the two eye-tracking studies on deaf readers. There was also evidence that handshape and movement overlap led to stronger activation of sign phonological representations, though the status of other sign phonological configurations (i.e., HLM, HL, and LM) are unclear. Finally, there was no converging evidence of visemic activation.

6.1.5 Implications for deaf education

As suggested in Marschark et al. (2011), deaf education should be approached based on an understanding of deaf people's unique cognitive needs and strengths. Therefore, it is important to consider what the studies presented in this thesis have told us about the cognitive needs and strengths of Hong Kong deaf readers and consider how approaches in Hong Kong deaf education might optimally interface with these.

Orthography and lexical quality

In Chapter 3, we saw that phonological processing deficits were only one part of a larger issue. This issue was that lower fluency deaf readers appeared to have lower quality lexical representations in their mental lexicons, which led to difficulties at multiple levels involving orthographic, phonological, and message-level processing. The fact that lower fluency deaf readers appeared to struggle more with activating word meanings based on orthographic cues is interesting as discussion of orthographic skills in deaf education seems to be overshadowed by debates surrounding the roles of spoken phonological code and sign language. Another reason that the importance of strong orthographic skills may be overlooked could be due to the fact that most research in deaf reading is based on readers of alphabetic scripts with less complex orthographies.

Chapter 1 touched on some developmental studies that show that visual skills are of special importance for Chinese reading development. For example, Huang and Hanley (1995) found that visual skills were more important for early reading development in Chinese children, while phonological skills were more important in reading development in British children. One study of reading development found that in Grade 1, visual skills correlate with reading level, but, in Grades 3–5, phonological awareness becomes a more important determinant of reading skill (Siok & Fletcher, 2001). Given that deaf readers showed a strong tendency to access word meanings through orthography, a tendency clearly demonstrated by the eye-tracking and ERP evidence presented in Chapters 2 and 4, respectively, it is likely that earlier deficits in orthographic knowledge or skill would have downstream negative effects on their development of high quality lexical representations with well-defined spoken phonological, sign phonological, and semantic constituents. As such, giving increased attention to early orthographic instruction for deaf children is likely to benefit their later reading development.

It should be noted, however, that orthographic deficits were only found in the Hong Kong deaf readers with lower reading fluency. Other studies have found deaf readers to have more efficient orthographic processing than hearing readers (Bélanger et al., 2013;

M. Yan et al., 2015), and in Chapter 4, we saw that deaf signers who acquired HKSL earlier in life appeared to have stronger parafoveal processing abilities. It is possible that earlier acquisition of sign language could also help contribute to later development of orthographic processing skills, possibly by way of improved visual spatial skills, which have been linked to higher sign language fluency (Talbot & Haude, 1993).

The role of phonological code

As previously discussed, based on the findings of the studies discussed in Chapters 3–5, Hong Kong deaf readers appear to use multiple types of phonological code. It may be that deaf readers might use these phonological codes in different ways. That is, sign phonological code may be used for early access to word meanings, while detailed (i.e., including sound and/or visual-tactile information) spoken phonological code may be used to integrate word meanings into syntax. Lastly, viseme-based phonological code may be used strategically when readers are trying to decipher unfamiliar or erroneous words.

In light of this, building on a foundation of strong orthographic skills, deaf readers of Chinese need to be given clear access to all phonological information associated with a given character including its pronunciation and sign translation. Of course, pronunciations need to be made fully accessible with unimpeded visual access to mouth shapes and romanization information. While deaf students do usually receive training in phonological skills, particularly during speech therapy, sign phonological skills might be overlooked. As demonstrated in Chapters 4 and 5, different sign phonological parameters seem to have different roles in facilitating lexical access. Therefore, ensuring that sign phonological representations are clearly defined in students' mental lexicons is important for helping them develop high quality lexical representations. To facilitate this, and in line with the view expressed in Petitto et al. (2016)—specialized training in sign phonology may lead to better overall reading outcomes.

6.1.6 Methodological issues and directions for future research

While the specific limitations of each study were addressed in their respective chapters, here I address some broader methodological issues. Firstly, it is important to consider the extent to which the findings of this research can be extended to deaf signers of different linguistic backgrounds. Given the diversity within and across different deaf communities, particularly in terms of linguistic and educational background, it is difficult to draw strong conclusions from research findings. This is especially true with regards to these current studies as the communication backgrounds of deaf signers can influence phonological processing in reading (see Koo et al., 2008). The Hong Kong deaf readers in these studies attended oral schools for the deaf and acquired HKSL through social interaction. Even among individuals who attended the same school (and had never attended mainstream school), some began using HKSL much later than others. It is likely that deaf signers who received their education primarily in oral language, like those who participated in the studies in Chapters 3–5, will exhibit unique patterns of phonological processing different to those of deaf signers who were educated through sign or orally-educated deaf non-signers. Additionally, given the unique sociolinguistic situation of Hong Kong (see Chapter 1)—namely the fact that people in Hong Kong all learn to read and write in Standard Written Chinese, a language that differs considerably from the most widely used spoken language, Cantonese—it would be wise to avoid using the results of these studies to make assumptions about readers of Chinese generally. Studies on what we referred to in Chapter 2 as “Cantonese reading” (referring to reading processes specific to Cantonese-dominant readers of Chinese) are still quite limited in number, so it is unclear how much Cantonese reading processes overlap with Chinese reading processes among Mandarin-dominant readers.

The studies in Chapters 4 and 5 focused specifically on the effects of different sign phonological parameters on reading processing. There are two reasons why we might not expect an identical pattern of results were similar studies to these conducted in other deaf communities. The first reason is that different sign phonological parameters are likely

to have different significance in different communities as there are clear phonological differences between different sign languages (for examples of such differences, see Lee et al., 2001). There was some indication, discussed in Chapter 4, that Hong Kong deaf signers might have different intuitions about sign phonological relatedness than signers of American Sign Language (ASL). Therefore, it is possible that users of different sign languages assign different levels of importance to each parameter, and this might reflect differences in how they use those parameters to store and access lexical items.

The second factor that might have influenced the outcomes of the current studies on sign phonological activation in reading is the relatively large number of sign variants used in Hong Kong. As most deaf schools in Hong Kong have closed, and more and more deaf students are being mainstreamed, the signing population is shrinking and the number of idiosyncratic signs used by different members of the Hong Kong deaf community are increasing (Sze et al., 2013). In some cases, when checking with signers to see how they expressed the target signs (when shown the target word), they would provide more than one variation. In cases where signers associate multiple signs with a single Chinese character or word, it is difficult to predict how this might affect their cognitive processing when exposed to that word. For example, are sign phonological features of all familiar variations activated, or do they only activate the form which they would produce? This question could not be answered from the Chapter 4 data as deaf participants were only asked to produce the sign as they would in daily conversation, and they were not tested on which variations they could recognize. This would be an interesting question to investigate in future studies, however.

In the following two subsections, some final issues related to the studies in this thesis will be addressed. These are areas where the studies could have been improved upon or are worth improving upon in future studies.

Sample, background, and norming issues

One difficulty we encountered was the limited number of deaf participants we could find to take part in the study. As many of the deaf participants took part in all of the experiments, it is possible that some noticed common patterns across the eye-tracking and ERP studies, which might have influenced how they read stimulus sentences. However, we took some steps to minimize such effects. First, the order of the eye-tracking experiments was counterbalanced such that half the participants completed the parafoveal preview study first, and the other half completed the error disruption study first. Second, the eye-tracking and ERP studies were spaced at least three weeks for each participant. Finally, participants were not informed of the aims of the experiments until after all experiments were completed.

As mentioned in Chapters 3, 4, and 5, we were unable to recruit matched hearing participants to take part in our studies as a comparison group. This was due to the fact that each study needed to be carried out over a limited period of time, and it was difficult to find age- and education-matched hearing participants who were able to travel to the university laboratory during the day (deaf participants were all working and had to be scheduled during after-work hours). This presents a difficulty for analysis. First, it would not have been appropriate to do a direct statistical comparison of the groups as any differences could be contributed to age, education, or reading fluency level rather than hearing status. Thus, we reported results from hearing readers simply as a point of reference to give readers a sense of how deaf participants compared to highly skilled hearing readers. This also served as a way to test our experiments—if patterns among hearing participants were in line with past studies on similar groups of readers, it would suggest that the experiments were appropriate for eliciting the targeted processes. In the discussions, direct comparisons of the groups were avoided, and any differences regarded as only suggestive. While analyses did not include effect sizes, this would have been another way to provide readers with a better picture of how the hearing readers differed from the deaf readers (for example, in terms of the time it took each group to resolve

homophonic errors, discussed in Chapter 3). It would be worth carrying out future studies with matched groups so that direct statistical comparisons of deaf and hearing Hong Kong readers could be made.

The studies carried out for this thesis did not include a measure of Cantonese oral language ability. Collecting such information can be difficult as it requires expertise in speech pathology, and one concern was that some deaf participants might not want to have their spoken Cantonese assessed (based on the author's knowledge that this can be a sensitive issue for some in the Hong Kong deaf community). However, if possible, collecting such information might be informative. It is possible that speech ability is connected with spoken phonological activation during reading. For example, phonological effects may be stronger in deaf readers with stronger speech skills. Self-reports might be another option for future studies if formal assessment is not possible.

Collecting familiarity ratings for Chinese words may have been more helpful than Character frequencies from the Hong Kong corpus. For example, the Chapter 4 study estimated word frequency by averaging the frequency of each of the two characters in the word. This was done as there is no publicly word-level frequency data available for Hong Kong written Chinese. Semantic ratings were estimated using HowNet (Dong et al., 2006). However, it also would have been better to obtain semantic similarity ratings for character pairs, as the HowNet data was not based on Hong Kong readers. Collecting more ratings for character pairs (e.g., semantic similarity, orthographic similarity, phonological similarity, and familiarity) from Hong Kong readers and pooling it into a database could be a very useful resource for researchers working on Cantonese reading.

Data analysis issues

First, for all eye-tracking studies, generalized linear mixed models were used for all analyses. The advantage of using these models is that they allow us to analyze our dependent variable without first applying a non-linear transformation to normalize the distribution of the data (see discussion on analysis in Chapter 3). While GLMMs are useful, they

can be unstable and prone to convergence errors. Using standard linear mixed models might have allowed for the use of more complex model structures, such as models that included random slopes. Tests on the data in the current thesis showed some limited success in this regard—random slopes on participants could be included in LMMs when they only included one fixed effect. Of course, this is a trade off as applying non-linear transformations can lead to loss of significant differences when those differences are found in the tails of the distributions (Lo & Andrews, 2015).

Pupillary response was used in the first study with hearing readers. The eye-tracking device used for the first study was ideal for measuring pupillary response data, while the Eyelink device used for the studies conducted in Hong Kong requires further processing (see Hayes & Petrov, 2016). While it was interesting to find the connection between orthographic processing and pupillary response, this information was not useful for addressing the research questions of the thesis, so pupillary response was dropped for the studies in Chapters 2 and 3.

In the analysis of the ERP data for Chapter 5, little was said regarding the sources of brain activity beyond stating the regions in which significant effects were found. One reason for this was that the primary aim of those studies was to investigate the time course of spoken and sign phonological activation. Furthermore, due to the limited number of closely related studies on deaf Chinese reading, it did not seem appropriate to form hypotheses regarding the regions that activity would occur. Without such hypotheses, drawing further post-hoc conclusions based on the regions in which significant activity was found can lead to faulty assumptions based on reverse inference (see Poldrack, 2006). Thus, regions of significant activity were reported without going much further, as was suggested by Luck (2014). Further research using functional neuroimaging techniques, such as functional magnetic resonance imaging (fMRI) or functional near-infrared spectroscopy (fNIRS), would be better for localizing the sources of brain activity during reading tasks.

Future research

The aim of this thesis was to answer a series of questions and build a picture of reading among deaf users of HKSL. The findings suggested that both Cantonese and HKSL phonology play a role in deaf reading, but the nature of that role still needs to be investigated. To better understand this, and further develop models of deaf reading (such as the one proposed in Chapter 3), it will be necessary to investigate how reading processing is affected when phonological codes are no longer available. One way of doing this is with the use of transcranial magnetic stimulation (TMS), which can be used to temporarily interfere with phonological processing while participants carry out word or sentence reading tasks (for example, as used in Costanzo et al., 2012). Developing this line of research could give us more insight into how readers are actually using phonological code and to what extent it actually contributes to reading comprehension.

Beyond this, there are three major directions for further research on deaf readers. Firstly, low-quality lexical representations were a factor associated with low levels of reading fluency. Future studies could be done with Hong Kong deaf readers to determine whether specific interventional strategies could be used to increase their knowledge of the orthographic and sign/spoken phonological forms associated with a given lexical item, and possibly lead to an overall increase in reading fluency. A second direction of research is to look at younger signers who do not have fully developed reading abilities. Looking at reading processing in developing deaf readers would be invaluable as it would provide insight into how use of orthographic and phonological information in reading changes over the course of literacy development. The third direction is to look for evidence of how sign language acquisition might confer cognitive processing advantages to deaf readers. In this thesis, we saw some evidence that parafoveal processing was more sensitive in deaf readers who acquired sign language at an earlier age. If future research supports this finding, it will serve as further evidence of the benefits of sign language acquisition on reading.

Finally, activation of sign phonological translations during Chinese reading might

parallel reading processes found in hearing L2 learners of Chinese. It is possible that L2 readers of Chinese activate phonological representations in their L1 (for example, in English) when reading Chinese characters. While the reverse has been attested to (Chinese phonological activation during English reading—see Thierry & Wu, 2007, Y. J. Wu & Thierry, 2010, 2012), this is less comparable to the process found in deaf readers of Chinese. Research investigating non-Chinese L1 phonological activation during L2 Chinese reading could potentially reveal similar patterns to what we have seen in deaf readers of Chinese.

6.2 Conclusion

This thesis has demonstrated that Hong Kong deaf readers, while showing a strong tendency to activate word meaning directly through orthography, also activate word meanings through spoken phonological and sign phonological representations. Furthermore, these findings suggest that sign phonological activation occurs at an earlier stage of processing than spoken phonological activation, which could indicate that deaf signers are using sign phonological representations to access word meanings and using spoken phonological representations to integrate meanings into their sentential context. Additionally, it was found that lower reading fluency among some deaf readers was associated with weaknesses in orthographic, phonological, and message-level processing, rather than being due purely to spoken phonological coding deficits.

A practical implication of this study is related to deaf education. Specifically, teaching Chinese vocabulary to deaf students requires balanced attention to the teaching of their associated orthographic, spoken phonological, and sign phonological forms, as well as imparting clear information about their meanings.

Appendices

6.3 Appendix 1

	FFD	GD	TRT
(Intercept)	431.97 (<i>SE</i> = 13.03, <i>t</i> = 33.15)	577.04 (<i>SE</i> = 14.03, <i>t</i> = 41.13)	979.76 (<i>SE</i> = 18.61, <i>t</i> = 52.66)
Ort	-41.31 (<i>SE</i> = 10.23, <i>t</i> = -4.04)	-103.05 (<i>SE</i> = 11.72, <i>t</i> = -8.79)	-246.91 (<i>SE</i> = 10.23, <i>t</i> = -24.14)
Hom	3.28 (<i>SE</i> = 8.25, <i>t</i> = 0.40)	2.57 (<i>SE</i> = 12.39, <i>t</i> = 0.21)	-185.58 (<i>SE</i> = 10.70, <i>t</i> = -17.34)
Cor	-100.36 (<i>SE</i> = 8.63 , <i>t</i> = -11.64)	-206.44 (<i>SE</i> = 11.82 , <i>t</i> = -17.46)	-494.82 (<i>SE</i> = 10.69 , <i>t</i> = -46.27)
PV	10.04 (<i>SE</i> = 7.50, <i>t</i> = 1.34)	5.85 (<i>SE</i> = 13.59, <i>t</i> = 0.43)	-14.31 (<i>SE</i> = 9.72, <i>t</i> = -1.47)
Ort × PV	5.36 (<i>SE</i> = 9.52, <i>t</i> = 0.56)	5.71 (<i>SE</i> = 10.67, <i>t</i> = 0.53)	10.50 (<i>SE</i> = 12.46, <i>t</i> = 0.84)
Hom × PV	-18.88 (<i>SE</i> = 9.77, <i>t</i> = -1.93)	-33.55 (<i>SE</i> = 11.22 , <i>t</i> = -2.99)	-35.60 (<i>SE</i> = 13.35 , <i>t</i> = -2.67)
Cor × PV	0.26 (<i>SE</i> = 9.31, <i>t</i> = 0.03)	-4.74 (<i>SE</i> = 12.07, <i>t</i> = -0.39)	14.22 (<i>SE</i> = 10.02, <i>t</i> = 1.42)
# of Observations	1727	1727	1714
logLik	-11386.80	-11955.77	-12608.82
AIC	22795.60	23933.55	25239.64

Table 6.1: *Full fixation time GLMMs*. Effect estimates with standard errors and *t*-values in parentheses. Significant interactions in **bold**. GLMM = Generalized linear mixed model. FFD = First fixation duration. GD = Gaze duration. TRT = Total reading time. Ort = Orthographic. Hom = Homophonic. Cor = Correct. PV = Predictability value.

	FFD	GD	TRT
TN	-2.16 (<i>SE</i> = 0.48 , <i>t</i> = -4.51)	-2.75 (<i>SE</i> = 0.72 , <i>t</i> = -3.80)	-0.84 (<i>SE</i> = 1.33, <i>t</i> = -0.63)
Ort × TN	3.53 (<i>SE</i> = 0.67 , <i>t</i> = 5.27)	4.31 (<i>SE</i> = 0.98 , <i>t</i> = 4.38)	2.85 (<i>SE</i> = 1.68, <i>t</i> = 1.70)
Hom × TN	0.60 (<i>SE</i> = 0.60, <i>t</i> = 1.00)	0.70 (<i>SE</i> = 0.95, <i>t</i> = 0.74)	-1.33 (<i>SE</i> = 1.53, <i>t</i> = -0.87)
Cor × TN	0.86 (<i>SE</i> = 0.57, <i>t</i> = 1.52)	1.52 (<i>SE</i> = 0.92, <i>t</i> = 1.67)	0.10 (<i>SE</i> = 1.39, <i>t</i> = 0.07)
# of Observations	1727	1727	1714
logLik	-11379.85	-11951.67	-12621.24
AIC	22781.71	23925.33	25262.48

Table 6.2: *Full fixation time GLMMs—trial effects*. Effect estimates with standard errors and *t*-values in parentheses. Significant interactions in **bold**. GLMM = Generalized linear mixed model. FFD = First fixation duration. GD = Gaze duration. TRT = Total reading time. Ort = Orthographic. Hom = Homophonic. Cor = Correct. PV = Predictability value.

	Pupil Diameter
(Intercept)	2.9940 ($SE = 0.08$, $t = 44.63$)
Ort	0.0288 ($SE = 0.01$, $t = 2.57$)
Hom	0.0095 ($SE = 0.01$, $t = 0.86$)
Unr	0.0068 ($SE = 0.01$, $t = 0.62$)
FN	0.0052 ($SE = 0.003$, $t = 1.99$)
Ort $\times$ FN	-0.0007 ($SE = 0.004$, $t = -0.21$)
Hom $\times$ FN	0.0003 ($SE = 0.004$, $t = 0.09$)
Unr $\times$ FN	-0.0001 ($SE = 0.004$, $t = -0.03$)
# of Observations	8436
logLik	3607.29
AIC	-7192.57

Table 6.3: *Full pupil diameter LMM*. Effect estimates with standard errors and t -values in parentheses. Significant interactions in **bold**. LMM = Linear mixed model. Ort = Orthographic. Hom = Homophonic. Unr = Unrelated. FN = Fixation number.

	Pupil Diameter
TN	-0.0039 ($SE = 0.0003$, $t = -13.27$)
Ort $\times$ TN	0.0012 ($SE = 0.0004$, $t = 3.08$)
Hom $\times$ TN	0.0001 ($SE = 0.0004$, $t = 0.35$)
Unr $\times$ TN	0.0001 ($SE = 0.0004$, $t = 0.39$)
# of Observations	8436
logLik	3920.85
AIC	-7817.70

Table 6.4: *Full pupil diameter LMM—trial effects*. Effect estimates with standard errors and t -values in parentheses. Significant interactions in **bold**. LMM = Linear mixed model. TN = Trial number. Ort = Orthographic. Hom = Homophonic. Unr = Unrelated.

6.4 Appendix 2

	FFD	GD	TRT
(Intercept)	259.51 (<i>SE</i> = 5.85, <i>t</i> = 44.33)	422.45 (<i>SE</i> = 6.83, <i>t</i> = 61.86)	1318.85 (<i>SE</i> = 54.59, <i>t</i> = 24.16)
Ort	-2.65 (<i>SE</i> = 4.63, <i>t</i> = -0.57)	-33.43 (<i>SE</i> = 6.03, <i>t</i> = -5.54)	-524.77 (<i>SE</i> = 44.34, <i>t</i> = -11.83)
Hom	-0.19 (<i>SE</i> = 4.79, <i>t</i> = -0.04)	-8.70 (<i>SE</i> = 6.23, <i>t</i> = -1.40)	-605.18 (<i>SE</i> = 43.20, <i>t</i> = -14.01)
Vis	1.23 (<i>SE</i> = 4.65, <i>t</i> = 0.26)	-10.23 (<i>SE</i> = 6.52, <i>t</i> = -1.57)	-310.56 (<i>SE</i> = 48.45, <i>t</i> = -6.41)
Cor	-41.50 (<i>SE</i> = 4.39, <i>t</i> = -9.45)	-152.03 (<i>SE</i> = 5.37, <i>t</i> = -28.32)	-871.33 (<i>SE</i> = 40.21, <i>t</i> = -21.67)
PV	-9.56 (<i>SE</i> = 3.76, <i>t</i> = -2.54)	-0.19 (<i>SE</i> = 4.98, <i>t</i> = -0.04)	-39.72 (<i>SE</i> = 37.48, <i>t</i> = -1.06)
Ort × PV	7.53 (<i>SE</i> = 4.57, <i>t</i> = 1.65)	-4.12 (<i>SE</i> = 6.08, <i>t</i> = -0.68)	4.88 (<i>SE</i> = 41.90, <i>t</i> = 0.12)
Hom × PV	0.36 (<i>SE</i> = 4.92, <i>t</i> = 0.07)	-16.11 (<i>SE</i> = 5.79, <i>t</i> = -2.78)	25.08 (<i>SE</i> = 40.67, <i>t</i> = 0.62)
Vis × PV	7.54 (<i>SE</i> = 5.09, <i>t</i> = 1.48)	5.40 (<i>SE</i> = 6.55, <i>t</i> = 0.82)	37.47 (<i>SE</i> = 47.28, <i>t</i> = 0.79)
Cor × PV	8.26 (<i>SE</i> = 4.48, <i>t</i> = 1.84)	0.93 (<i>SE</i> = 4.70, <i>t</i> = 0.20)	50.36 (<i>SE</i> = 38.35, <i>t</i> = 1.31)
# of Observations	2676	2676	2676
logLik	-15717.82	-17648.12	-20049.02
AIC	31461.64	35322.24	40124.05

Table 6.5: *GLMMs for hearing readers*. Effect estimates with standard errors and *t*-values in parentheses. Significant interactions in **bold**. GLMM = generalized linear mixed model. FFD = first fixation duration. GD = gaze duration. TRT = total reading time. Ort = orthographic. Hom = homophonic. Vis = homovisemic. Cor = correct. PV = predictability value.

	FFD	GD	TRT
(Intercept)	267.55 (<i>SE</i> = 7.58, <i>t</i> = 35.29)	383.29 (<i>SE</i> = 6.67, <i>t</i> = 57.44)	1257.92 (<i>SE</i> = 118.85, <i>t</i> = 10.58)
Ort	-17.89 (<i>SE</i> = 5.35, <i>t</i> = -3.34)	-35.66 (<i>SE</i> = 5.83, <i>t</i> = -6.11)	-423.15 (<i>SE</i> = 74.28, <i>t</i> = -5.70)
Hom	-9.37 (<i>SE</i> = 5.13, <i>t</i> = -1.83)	-5.21 (<i>SE</i> = 7.00, <i>t</i> = -0.74)	-167.38 (<i>SE</i> = 82.78, <i>t</i> = -2.02)
Vis	-0.32 (<i>SE</i> = 5.32, <i>t</i> = -0.06)	-8.37 (<i>SE</i> = 7.41, <i>t</i> = -1.13)	-178.33 (<i>SE</i> = 82.17, <i>t</i> = -2.17)
Cor	-33.35 (<i>SE</i> = 4.63, <i>t</i> = -7.20)	-100.33 (<i>SE</i> = 6.60, <i>t</i> = -15.20)	-799.21 (<i>SE</i> = 65.79, <i>t</i> = -12.15)
PV	0.53 (<i>SE</i> = 3.75, <i>t</i> = 0.14)	12.04 (<i>SE</i> = 5.10, <i>t</i> = 2.36)	20.57 (<i>SE</i> = 64.60, <i>t</i> = 0.32)
Ort × PV	6.55 (<i>SE</i> = 5.11, <i>t</i> = 1.28)	-15.39 (<i>SE</i> = 6.12, <i>t</i> = -2.52)	-16.74 (<i>SE</i> = 75.69, <i>t</i> = -0.22)
Hom × PV	-3.46 (<i>SE</i> = 5.00, <i>t</i> = -0.69)	-12.87 (<i>SE</i> = 6.47, <i>t</i> = -1.99)	-154.72 (<i>SE</i> = 75.19, <i>t</i> = -2.06)
Vis × PV	7.56 (<i>SE</i> = 5.30, <i>t</i> = 1.43)	26.11 (<i>SE</i> = 6.11, <i>t</i> = 4.27)	24.66 (<i>SE</i> = 85.92, <i>t</i> = 0.29)
Cor × PV	-10.60 (<i>SE</i> = 4.89, <i>t</i> = -2.17)	-19.73 (<i>SE</i> = 5.35, <i>t</i> = -3.69)	-22.71 (<i>SE</i> = 66.58, <i>t</i> = -0.34)
RTS	-3.37 (<i>SE</i> = 10.05, <i>t</i> = -0.34)	-40.64 (<i>SE</i> = 8.03, <i>t</i> = -5.06)	-71.28 (<i>SE</i> = 147.11, <i>t</i> = -0.48)
Ort × RTS	-11.47 (<i>SE</i> = 6.31, <i>t</i> = -1.82)	-9.76 (<i>SE</i> = 7.07, <i>t</i> = -1.38)	-278.19 (<i>SE</i> = 96.39, <i>t</i> = -2.89)
Hom × RTS	-11.42 (<i>SE</i> = 6.05, <i>t</i> = -1.89)	-29.92 (<i>SE</i> = 6.88, <i>t</i> = -4.35)	-184.51 (<i>SE</i> = 106.45, <i>t</i> = -1.73)
Vis × RTS	1.73 (<i>SE</i> = 6.04, <i>t</i> = 0.29)	-5.17 (<i>SE</i> = 7.38, <i>t</i> = -0.70)	-130.47 (<i>SE</i> = 104.54, <i>t</i> = -1.25)
Cor × RTS	-7.11 (<i>SE</i> = 5.30, <i>t</i> = -1.34)	-15.67 (<i>SE</i> = 7.47, <i>t</i> = -2.10)	-237.43 (<i>SE</i> = 83.85, <i>t</i> = -2.83)
PV × RTS	5.20 (<i>SE</i> = 3.83, <i>t</i> = 1.36)	-10.11 (<i>SE</i> = 5.08, <i>t</i> = -1.99)	-1.01 (<i>SE</i> = 81.56, <i>t</i> = -0.01)
Ort × PV × RTS	2.10 (<i>SE</i> = 5.59, <i>t</i> = 0.38)	-13.20 (<i>SE</i> = 7.57, <i>t</i> = -1.74)	-32.12 (<i>SE</i> = 99.47, <i>t</i> = -0.32)
Hom × PV × RTS	-3.80 (<i>SE</i> = 5.78, <i>t</i> = -0.66)	27.07 (<i>SE</i> = 7.05, <i>t</i> = 3.84)	-51.36 (<i>SE</i> = 97.97, <i>t</i> = -0.52)
Vis × PV × RTS	8.89 (<i>SE</i> = 6.52, <i>t</i> = 1.36)	48.02 (<i>SE</i> = 6.69, <i>t</i> = 7.17)	129.62 (<i>SE</i> = 111.01, <i>t</i> = 1.17)
Cor × PV × RTS	-15.25 (<i>SE</i> = 5.79, <i>t</i> = -2.63)	-2.80 (<i>SE</i> = 6.22, <i>t</i> = -0.45)	-7.65 (<i>SE</i> = 87.16, <i>t</i> = -0.09)
# of Observations	2766	2766	2766
logLik	-16226.36	-18269.57	-21643.65
AIC	32498.71	36585.14	43333.29

Table 6.6: *GLMMs for deaf readers*. Effect estimates with standard errors and *t*-values in parentheses. Significant interactions in **bold**. GLMM = generalized linear mixed model. FFD = first fixation duration. GD = gaze duration. TRT = total reading time. Ort = orthographic. Hom = homophonic. Vis = homovisemic. Cor = correct. PV = predictability value. RTS = reading test score.

6.5 Appendix 3

	FFD	GD	TRT
(Intercept)	274.24 ($SE = 10.23, t = 26.82$)	358.86 ($SE = 10.27, t = 34.96$)	619.91 ($SE = 10.03, t = 61.81$)
Sign Phonological	6.93 ($SE = 5.70, t = 1.22$)	5.14 ($SE = 7.25, t = 0.71$)	-2.13 ($SE = 11.91, t = -0.18$)
Identical	-51.04 ($SE = 5.12, t = -9.97$)	-89.61 ($SE = 6.71, t = -13.35$)	-166.56 ($SE = 11.18, t = -14.90$)
# of Observations	1877	1877	1853
logLik	-11281.06	-12049.16	-12810.84
AIC	22574.12	24110.32	25633.67

Table 6.7: *First set of GLMMs for Study 1 (hearing readers)*. Effect estimates with standard errors and t -values in parentheses. Significant interactions in **bold**. GLMM = generalized linear mixed model. FFD = first fixation duration. GD = gaze duration. TRT = total reading time.

	FFD	GD	TRT
(Intercept)	274.29 ($SE = 9.16, t = 29.96$)	358.86 ($SE = 17.66, t = 20.32$)	620.04 ($SE = 14.47, t = 42.85$)
HLM	15.25 ($SE = 9.68, t = 1.58$)	9.99 ($SE = 17.43, t = 0.57$)	-1.11 ($SE = 9.95, t = -0.11$)
HL	9.25 ($SE = 8.27, t = 1.12$)	9.47 ($SE = 14.05, t = 0.67$)	-0.05 ($SE = 12.21, t = -0.00$)
HM	-7.30 ($SE = 8.13, t = -0.90$)	4.70 ($SE = 15.13, t = 0.31$)	7.62 ($SE = 32.47, t = 0.23$)
LM	11.04 ($SE = 9.74, t = 1.13$)	-2.87 ($SE = 11.94, t = -0.24$)	-15.16 ($SE = 12.75, t = -1.19$)
Identical	-51.12 ($SE = 4.99, t = -10.24$)	-89.54 ($SE = 8.28, t = -10.81$)	-166.50 ($SE = 8.33, t = -19.98$)
# of Observations	1877	1877	1853
logLik	-11279.40	-12048.92	-12810.59
AIC	22576.81	24115.85	25639.18

Table 6.8: *Second set of GLMMs for Study 1 (hearing readers)*. Effect estimates with standard errors and t -values in parentheses. Significant interactions in **bold**. GLMM = generalized linear mixed model. FFD = first fixation duration. GD = gaze duration. TRT = total reading time.

	FFD	GD	TRT
(Intercept)	262.24 ($SE = 9.99, t = 26.26$)	359.17 ($SE = 13.16, t = 27.29$)	682.75 ($SE = 10.37, t = 65.83$)
Sign Phonological	4.01 ($SE = 4.97, t = 0.81$)	7.21 ($SE = 6.83, t = 1.06$)	2.44 ($SE = 9.42, t = 0.26$)
Identical	-27.54 ($SE = 4.71, t = -5.85$)	-49.37 ($SE = 6.26, t = -7.88$)	-129.19 ($SE = 8.79, t = -14.71$)
# of Observations	1954	1954	1915
logLik	-11569.90	-12520.38	-13515.44
AIC	23151.80	25052.75	27042.89

Table 6.9: *First set of GLMMs for Study 2 (deaf readers)*. Effect estimates with standard errors and t -values in parentheses. Significant interactions in **bold**. GLMM = generalized linear mixed model. FFD = first fixation duration. GD = gaze duration. TRT = total reading time.

	FFD	GD	TRT
(Intercept)	262.24 ($SE = 6.94, t = 37.76$)	358.76 ($SE = 10.61, t = 33.81$)	681.79 ($SE = 11.54, t = 59.08$)
HLM	3.49 ($SE = 7.38, t = 0.47$)	18.20 ($SE = 9.05, t = 2.01$)	43.48 ($SE = 9.88, t = 4.40$)
HL	0.93 ($SE = 6.58, t = 0.14$)	-17.54 ($SE = 8.94, t = -1.96$)	-39.99 ($SE = 9.88, t = -4.05$)
HM	16.62 ($SE = 6.93, t = 2.40$)	37.86 ($SE = 11.72, t = 3.23$)	46.91 ($SE = 10.46, t = 4.48$)
LM	-3.76 ($SE = 6.69, t = -0.56$)	-2.88 ($SE = 9.18, t = -0.31$)	-25.83 ($SE = 9.83, t = -2.63$)
Identical	-27.54 ($SE = 4.32, t = -6.38$)	-49.29 ($SE = 5.80, t = -8.50$)	-128.26 ($SE = 8.71, t = -14.72$)
# of Observations	1954	1954	1915
logLik	-11568.25	-12515.83	-13511.10
AIC	23154.50	25049.65	27040.20

Table 6.10: *Second set of GLMMs for Study 2 (deaf readers)*. Effect estimates with standard errors and t -values in parentheses. Significant interactions in **bold**. GLMM = generalized linear mixed model. FFD = first fixation duration. GD = gaze duration. TRT = total reading time.

	FFD	GD	TRT
AoA	-3.34 ($SE = 2.33, t = -1.43$)	-5.71 ($SE = 3.56, t = -1.60$)	-15.74 ($SE = 7.76, t = -2.03$)
AoA $\times$ HLM	-0.97 ($SE = 1.97, t = -0.49$)	-1.28 ($SE = 2.84, t = -0.45$)	-6.17 ($SE = 4.09, t = -1.51$)
AoA $\times$ HL	1.82 ($SE = 1.96, t = 0.93$)	3.42 ($SE = 2.57, t = 1.33$)	5.54 ($SE = 4.10, t = 1.35$)
AoA $\times$ HM	-0.28 ($SE = 1.87, t = -0.15$)	4.96 ($SE = 3.16, t = 1.57$)	2.16 ($SE = 5.28, t = 0.41$)
AoA $\times$ LM	1.28 ($SE = 1.90, t = 0.67$)	4.12 ($SE = 2.61, t = 1.58$)	-1.39 ($SE = 3.93, t = -0.35$)
AoA $\times$ Identical	2.29 ($SE = 1.25, t = 1.83$)	2.81 ($SE = 1.69, t = 1.66$)	4.99 ($SE = 2.61, t = 1.91$)
# of Observations	1954	1954	1915
logLik	-11565.71	-12513.57	-13507.74
AIC	23161.42	25057.15	27045.48

Table 6.11: *Third set of GLMMs for Study 2 (deaf readers—age of acquisition effects)*. Effect estimates with standard errors and t -values in parentheses. Significant interactions in **bold**. GLMM = generalized linear mixed model. FFD = first fixation duration. GD = gaze duration. TRT = total reading time. H = handshape. L = location. M = movement. AoA = age of acquisition.

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- This article proposes a model of reading specific to deaf readers based on the dual route cascaded model of reading aloud. The primary different between the two is

that the current model proposes that deaf readers' phonological representations are based on the unit of viseme rather than phoneme. Visemic representations are primarily developed based on visual (and possibly some tactile) features of the phoneme as it is pronounced. As auditory information is reduced, phonemes such as /p/, /b/, and /m/ are represented by a single viseme /P/. Of course, this might vary among deaf people depending on their speech reading skills and residual hearing levels. Their study to test this hypothesis used a lexical decision task using real words, pseudo-homovisemes and spelling controls. The deaf participants took longer to rejected the pseudo-homovisemes as non-words than spelling controls, supporting their claim.

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