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

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ABSTRACT

This study investigated Cantonese and Hong Kong Sign Language (HKSL) phonological activation patterns in Hong Kong deaf readers using the ERP technique. Two experiments employing the error disruption paradigm were conducted while recording participants' EEGs. Experiment 1 focused on orthographic and speech-based phonological processing, while Experiment 2 examined sign-phonological processing. ERP analyses focused on the P200 (180–220 ms) and N400 (300–500 ms) components.

The results of Experiment 1 showed that hearing readers exhibited both orthographic and phonological effects in the P200 and N400 windows, consistent with previous studies on Chinese reading. In deaf readers, significant speech-based phonological effects were observed in the P200 window, and orthographic effects spanned both the P200 and N400 windows. Comparative analysis between the two groups revealed distinct spatial distributions for orthographic and speech-based phonological ERP effects, which may indicate the engagement of different neural networks during early processing stages.

Experiment 2 found evidence of sign-phonological activation in both the P200 and N400 windows among deaf readers, which may reflect the involvement of sign-phonological representations in early lexical access and later semantic integration. Furthermore, exploratory analysis revealed that higher reading fluency in deaf readers correlated with stronger orthographic effects in the P200 window and diminished effects in the N400 window, indicating that efficient orthographic processing during early lexical access is a distinguishing feature of proficient deaf readers.

1. Introduction

Research on deaf bimodal bilinguals, individuals who know both a signed and spoken (possibly in written form only) language, has formed a complex picture of deaf reading processes, particularly regarding their use of phonological code. For example, there is evidence that bimodal bilingual deaf readers can activate both spoken-language phonological representations (Gutierrez-Sigut, Vergara-Martínez, & Perea, 2017; Hanson & Lichtenstein, 1990; Thierfelder, Wigglesworth, & Tang, 2020a; Yan, Pan, Bélanger, & Shu, 2015) and sign-phonological representations (Chiu, Kuo, Lee, & Tzeng, 2016; Chiu & Wu, 2016; Kubus, Villwock, Morford, & Rathmann, 2015; Meade, Midgley, Sevcikova Sehyr, Holcomb, & Emmorey, 2017; Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Pan, Shu, Wang, & Yan, 2015; Thierfelder, Wigglesworth, & Tang, 2020b) associated with the words they are reading.

The extent to which deaf readers activate speech-based phonological code during reading is still a topic of investigation. Some researchers have reported finding little to no evidence of this in their experiments involving deaf readers (Bélanger, Baum, & Mayberry, 2012; Bélanger, Mayberry, & Rayner, 2013). However, several studies have indicated that some deaf readers activate speech-based phonological code during reading; however, the degree of this activation for individual words is modulated by factors such as their contextual predictability, the duration of fixation, and the reader's proficiency level (Thierfelder, Wigglesworth, & Tang, 2020a; Yan et al., 2015; Yan, Lan, Wang, & Benson, 2020).

1.1. Orthographic processing in deaf readers

In a review investigating the neurocognitive attributes of proficient deaf readers, Emmorey and Lee (2021) suggest that, in contrast to hearing readers, deaf readers depend more on direct orthographic-semantic connections rather than phonology and demonstrate increased engagement of the right hemisphere during the complex processes underlying word recognition. Although the activation of speech-based phonology in deaf readers may vary across different deaf

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populations depending on their individual linguistic experiences, a growing body of research suggests that deaf readers exhibit a more pronounced reliance on orthography and develop stronger connections between orthographic and semantic representations compared to hearing readers. In an eye-tracking study investigating Chinese reading, Yan et al. (2015) found that deaf readers can more efficiently activate semantic representations from characters visible in the parafovea compared to hearing readers. In a structural priming study by Cai, Zhao, Lin, Xu, and Thierfelder (2022), deaf readers of Chinese were presented with written Chinese primes and asked to complete a two-step task: first, they re-typed the full prime sentence; next, they were shown a picture and prompted to type a description sentence following a given preamble. The deaf participants showed enhanced structural priming effects for homographic prime-target homophone pairs, but not for heterographic pairs, leading the authors to conclude that orthography, rather than speech-based phonology, plays a primary role in the development and organization of lexical representations in deaf individuals.

Beyond simply having increased reliance on orthographic-semantic connections and more efficient orthographic processing, some research suggests that deaf and hearing readers may utilize certain distinct mechanisms for processing orthography. Emmorey, Holcomb, and Midgley (2021) observed that deaf readers demonstrated an increased sensitivity to differences in letter casing between prime and target words compared to hearing readers and suggested that the mechanism for abstract letter representation in deaf readers may differ fundamentally from that in hearing readers. Gutierrez-Sigut, Vergara-Martínez, and Perea (2022) found that deaf readers are more sensitive to subtle visual features during word recognition, potentially reflecting fundamental differences in the visual-orthographic processing systems of deaf and hearing readers.

In a large-scale character-decision study, Thierfelder, Cai, Huang, and Lin (2023) found that, in deaf readers, increased orthographic complexity (i.e., higher stroke counts) of Chinese characters had a facilitative effect on character recognition, leading to higher accuracy and faster reaction times. In hearing readers, character complexity had the opposite effect, with performance decreasing as complexity increased. The authors conclude that these contrasting patterns suggest that deaf readers may employ unique cognitive mechanisms or strategies during orthographic processing.

1.2. Models of deaf reading

Researchers have explicated reading processes in deaf individuals using cognitive models. Elliott, Braun, Kuhlmann, and Jacobs (2012), for example, extended the dual-route model (Coltheart, 2005, 2006; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) to describe spoken language 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 meanings 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 lip reading (or *speechreading*). Thus, when the indirect phonological route to meaning is utilized, deaf readers 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, Hermans, Knoors, and Verhoeven (2012). 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 speech- and sign-based phonological activation in deaf readers, the relationship between these speech-based and sign-based phonological systems remains ambiguous. For example, it is unclear if deaf readers preferentially activate one type of phonological code over the other, nor do we know if these codes are activated simultaneously or at different stages of processing. The current study aims to explore these questions through two Chinese reading experiments focused on adult deaf readers from Hong Kong. Experiment 1 investigates orthographic and speech-based phonological processing, and Experiment 2 investigates sign-phonological processing.

1.3. 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, Fan, & Fei, 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 primarily used to describe reading in English and other alphabetic languages can also be applied to Chinese reading. Addressing this issue, Perfetti, Liu, and Tan (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 script, we automatically activate the orthographic, phonological, and semantic representations associated with that word. However, phonological activation in reading alphabetic scripts 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 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.

1.4. Eye fixations

1.4.1. 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 are replaced with orthographically related or homophonic (or phonologically related) 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, Miller, Shu, & Zhang,

[1] Cantonese pronunciations are written in the Jyutping romanization system.

2001; Wong & Chen, 1999; Zhou, Shu, Miller, & Yan, 2018). There is some evidence, though, that earlier phonological activation can be facilitated by high levels of contextual constraint (Thierfelder, Durantin, & Wigglesworth, 2020; Thierfelder, Wigglesworth, & Tang, 2020a).

In a study that used an error disruption paradigm with eye-tracking and focused specifically on adult deaf readers of Chinese, Thierfelder, Wigglesworth, and Tang (2020a) investigated how deaf readers use orthographic, speech-based 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 lip reading. 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 lip reading 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, and Tang (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. (2012) dual-route cascaded model of reading by deaf adults in that it suggested some limited use of visemic code, though only in certain circumstances (i.e., re-reading for error recovery) or readers (i.e., lower-fluency deaf readers).

1.4.2. *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, Angele, & Rayner, 2012, and Vasilev & Angele, 2017, for an overview). In this paradigm, a target word, which is preceded by an invisible boundary, is substituted with a 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, Kliegl, & Yan, 2012; Tsai, Lee, Tzeng, Hung, & Yen, 2004; Yan, Richter, Shu, & Kliegl, 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, Laubrock, and Yan (2016) and 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 to be handshape, location, and movement (Stokoe, Casterline, & Croneberg, 1965). Hand orientation and facial expressions (or non-manual features) have been identified as additional parameters, but most cognitive research has focused on those of handshape, location, and movement.

Pan et al. (2015) were 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 et al. (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, and Tang (2020b) carried out a parafoveal preview study that used four types of sign-phonologically related preview words, 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), and 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.

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 when 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, these studies suggest that while the effects of sign-phonological activation can emerge as early

as the first fixation on a target, the effects of speech-based phonological activation tend to emerge later—in gaze duration, at the earliest. However, this was only found in certain circumstances (e.g., when contextual constraint is high or among highly fluent readers).

1.4.3. Event-related potentials

Event-related potentials (ERPs) are useful for investigating the time course of orthographic and phonological activation during 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 the stimulus onset and has been associated with the early extraction of words' orthographic and phonological features (Barnea & Breznitz, 1998; Sereno, Rayner, & Posner, 1998). The N400 is a negative ERP wave that peaks around 400 ms after the stimulus onset and reflects incongruity between a word and its context (Connolly, Phillips, & Forbes, 1995; Kutas & Hillyard, 1980).

In ERP studies on silent Chinese word and sentence reading, the P200 and N400 components have been associated with orthographic, phonological, and semantic processing. Using semantic and homophone judgment tasks, Zhang, Zhang, and Kong (2009) 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, Zhang, Zhang, and Kang (2012) conducted a primed semantic judgment study using orthographically-related pairs that were unrelated in 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 used the error disruption paradigm to conduct sentence-reading studies with ERPs. Ren, Liu, and Han (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, Jin, Qing, and Wang (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 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 Chinese readers, Li, Liu, Liu, Zhang, and Yang (2017) found evidence of spoken-phonological activation among deaf readers, which emerged in the N400. However, this effect emerged earlier in the N200/P200 components for hearing readers. 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 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 judgment times were longer. They concluded that, while slower RTs in the semantic judgment task reflected sign-phonological interference at the task-level, the reduced N400 reflected the initial activation of the sign translation.

These studies demonstrate the effectiveness of the ERP technique in exploring orthographic and phonological activation processes, which influence the wave amplitudes of the P200 and N400 components during Chinese reading. Additionally, the N400 component has been shown to reflect both speech- and sign-based phonological processing in deaf readers. However, no studies have used ERPs to investigate both spoken and sign-phonological processing during sentence reading in deaf Chinese readers.

2. The present study

Evidence from both eye-movement recordings and ERPs has shown that deaf readers can activate spoken language and sign language 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 ascertain whether both types of phonological code are activated along a similar time course or whether they are activated asynchronously. In Thierfelder, Wigglesworth, and Tang (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, and Tang (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. When taken together, these findings point to the possibility that deaf readers activate sign phonology at an earlier stage of processing than spoken phonology.

This study uses two error disruption paradigms with ERPs to investigate the time course of orthographic, speech-based phonological, and sign-phonological activation during Chinese sentence reading. Experiment 1 focuses on orthographic and speech-based phonological activation by including correct, orthographically-related, homophonic, homovisemic, 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, and Tang (2020b) and Thierfelder, Wigglesworth, and Tang (2020a), this study hypothesizes 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, & Tang, 2020a; Yan et al., 2015), it is also expected that orthographic effects will emerge early in the P200.

2.1. Experiment 1 method

2.1.1. Sampling plan

In response to reviewer feedback on an earlier version of this paper, a power analysis was conducted using simulations to establish an adequate sample size for the matched hearing group.[2] After collecting data from the first 12 hearing participants, three reduced linear mixed models[3] were built for each ERP component (P200 and N400) and each experiment using the lme4 package (Bates et al., 2015) in the R statistical environment (R Core Team, 2023). These models were then used to create an expanded data set with simulated data for 80 participants using the SIMR package (Green & MacLeod, 2016).

The *powerCurve()* function in SIMR was employed using the simulated dataset to estimate how the power of significance tests changes as the sample size increases from 3 to 80 participants. The power analysis revealed that a sample size of 40 hearing participants would provide sufficient statistical power (approximately 80%) to detect significant interactions between Condition and Hemisphere, as well as Condition and Lobe, for both the P200 and N400 components in Experiment 1.

With 40 hearing participants, however, the statistical power for detecting an overall effect of condition was just over 40%. The power analysis indicated that >80 hearing participants would be required to achieve 80% power for this effect. In order to balance the need for adequate statistical power with maintaining comparable group sizes, a sample size of 40 hearing participants was chosen, which allowed for sufficient power to detect interactions between Condition and Hemisphere, as well as Condition and Lobe. However, it is important to note that the power to detect an overall effect of condition fell below the desired 80% threshold.

It is important to note that a power analysis was not performed for the deaf group, as 80% of their data had already been collected by the time the reviewer feedback was received. Furthermore, recruiting additional fluent deaf signers had become a significant challenge due to the limited population size and the specific inclusion criteria for the study. Therefore, the final sample size of 30 for the deaf group was based on the number of participants that could be realistically recruited within the study's timeframe. Power curves for Experiment 1 can be found in Fig. A1 in the appendix.

2.1.2. Participants and background measures

Thirty participants with severe to profound hearing loss, ranging from 80 to 120 dB, took part in the experiment. All deaf participants began attending an oral deaf school at the elementary school level and had completed secondary school. Nine had an undergraduate degree. Deaf participants reported that they used HKSL for day-to-day communication but varied widely in terms of when they first began learning it. Ten 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 limited exposure prior to that). The mean age of HKSL acquisition (HKSL AoA) was 4.2 years old ($SD = 3.7$). Deaf participants ranged in age from 28 to 46 ($M = 37.1$, $SD = 5.4$).

A sample of 40 hearing participants, matched with the deaf group for age, education, and reading fluency, were recruited as a comparison group. The hearing group had a mean age of 36 (range: 27–46, $SD = 5.1$) years old, and ages were not significantly different between the two groups [$t(60) = 0.67$, $p = .502$]. Hearing participants were native speakers of Cantonese who had been born and educated in Hong Kong. All hearing participants reported having completed secondary school, and 14 had completed an undergraduate degree. The deaf and hearing groups did not differ significantly in the number of undergraduate degree holders [$\chi^2(1, N = 70) = 0.03$, $p = .854$]. 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 designed based on those described in Moll, Fussenegger, Willburger, and Landerl (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 quickly as they could, aiming to read as many as possible within two minutes while marking each as correct or incorrect. Each participant's final reading fluency scores were calculated as the number of characters contained within the correctly judged sentences. Scores indicated that deaf participants read at an average rate of about 146 ($SD = 50.8$) characters per minute. Hearing participants read at an average rate of 152 characters per minute ($SD = 45.9$), which did not differ significantly from the deaf participants [$t(59) = -0.48$, $p = .636$]. A summary of participant backgrounds is presented in Table 1.

Ethical clearance for this study was granted by the author's university, 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.

2.1.3. 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 this condition) 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, Dong, & Hao, 2006), a Chinese semantic database for natural language processing that can produce similarity ratings in line with human judgments (Dai, Liu, Xia, & Wu, 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 [$F(3, 94) = 0.42$, $p = .743$]. The number of strokes per character was also matched across conditions [$F(4, 120) = 0.61$, $p = .660$]. Due to the limited number of characters that could be used as orthographic, homophonic, and homovisemic substitutions, these characters tended to be of lower frequency[4] than the correct characters. Importantly, however, there were

Table 1
Backgrounds of deaf and hearing participants. This table presents the number of participants (N), mean ages, ages of HKSL acquisition (deaf group only), reading fluency scores (average number of Chinese characters per minute), and percentage of undergraduate degree holders for both deaf and hearing groups. *SD*s are in parentheses.

Group	N	Age	HKSL AoA	Reading score	Degree holders (%)
Deaf	30	37.1 (5.4)	4.2 (3.7)	146 (50.8)	30%
Hearing	40	36.2 (4.9)	–	152 (45.9)	35%

[2] In the previous iteration of this study, data was collected from a group of 24 deaf participants and a group of 24 hearing participants who were significantly younger and had higher reading fluency levels. For better comparability, new data was collected from the current group of hearing participants matched with the deaf participants for age and reading fluency.

[3] Reduced linear mixed models were specified as follows:1. P200/N400 ~ Condition + Trial + (1 | Participant)2. P200/N400 ~ Condition × Hemisphere + Trial + (1 | Participant)3. P200/N400 ~ Condition × Lobe + Trial + (1 | Participant)

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

no significant differences in frequency across the orthographic, homophonic, homovisemic, and unrelated substitution characters [$F(3, 96) = 1.93$, $p = .131$].

For the homovisemic condition, characters were not distinguishable from correct mates through lip-reading 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 lip-reading. 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/). 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 2 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 [$F(3, 57) = 121.82$, $p < .001$]. Characters in the orthographic condition were rated as more similar to their correct mates compared to the other three error types ($ps < 0.001$), which were not significantly different from each other ($ps > 0.1$). All character properties are summarized in Table 2.

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 ($M = 10$, $SD = 1.5$).

Following prior ERP studies on Chinese sentence reading (e.g., Liu et al., 2011; Ren et al., 2009), sentence contexts were designed to make the terminal character predictable. In order to validate the predictability of these characters, a cloze test 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. In one case, there were 0 correct guesses for the sentence. Of the remaining sentences, the percentage of correct guesses per sentence frame ranged from five to 100% and was high overall, with an average of 75% ($SD = 30\%$) correct guesses. Only nine sentences were in the low range of below 25% correct predictions. Based on the author's consultation with native Chinese speakers, changing the word or sentence frames would not likely have improved target predictability in these specific cases, so they were retained in the final experiment as not to decrease the overall number of items.[5] To help control for potential confounding effects of varying levels of predictability on the ERP measures, standardized predictability values (i.e., the number of correct guesses) were included as a covariate in the statistical models (see *Analysis*).

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 once 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 3 shows an example sentence frame in each of the five conditions. As this study included some readers with low reading proficiency, who are more likely to experience reading fatigue, filler sentences were not used in order to limit the experiment's length.

2.1.4. 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 (∼***∼) was visible in the center of the screen 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 on the screen after approximately one-fifth of the sentences to encourage participants to read for meaning (for example: 前一句有沒有提到「魚」? *Did the last sentence mention "fish"?*). Both hearing and deaf groups were able to answer with a reasonable degree of accuracy (hearing average score: $M = 88\%$, $SD = 14\%$; deaf average score: $M = 82\%$, $SD = 12\%$). Hearing participants had a higher average, but the difference between the two groups did not reach significance [$t(67) = -1.76$, $p = .082$]. 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.

2.1.5. 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 kΩ, 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, Mullen, Kothe, Su, & Robbins, 2015) was used to remove and interpolate bad channels automatically, and a high pass filter of 0.01 Hz was applied to the continuous data. After conducting independent component analysis (ICA), the ICLabel plugin (Pion-Tonachini, Kreutz-Delgado, & Makeig, 2019) within EEGLAB was used to classify non-brain activity automatically. These components were removed after carrying out blink detection (see below).

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 prestimulus window. In order to remove trials containing blinks (during which participants may have missed the target stimuli), epochs containing artifacts exceeding 100 μV were detected and rejected using ERPLAB's moving window peak-to-peak artifact rejection function with a window size of 100 ms and step size of 50 ms. Additionally, any epochs with residual voltage excursions beyond ±150 μV that were not detected by the moving window technique were identified using a simple voltage threshold method and then removed. The artifact removal process resulted in discarding an average of 11% of trials for each hearing participant (SD = 12%) and 10% for each deaf participant (SD = 6%). A low pass filter of 30 Hz was applied temporarily during blink detection

[5] The number of possible character sets that fit the experiment's design requirements were very limited. Devising alternative character sets would have required the use of obscure characters with which many less skilled readers would most likely not be familiar.

Table 2
Experiment 1 character properties. Mean frequencies are from Ho and Kwan (2001). Semantic similarity ratings were calculated using the HowNet database (Dong et al., 2006). *SD*s are in parentheses.

	Correct	Orthographic	Homophonic	Homovisemic	Unrelated
Example	上 /soeng6/ [above]	止 /zi2/ [stop]	尚 /soeng6/ [esteem]	丈 /zoeng6/ [husband]	以 /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	–	0.12 (0.21)	1 (0)	0.66 (0.15)	0.19 (0.19)
Semantic Relatedness	–	0.36 (0.36)	0.27 (0.29)	0.31 (0.36)	0.31 (0.36)
Stroke Count	6.4 (3.7)	6.8 (4.2)	7.9 (3.7)	7.1 (4.9)	6.9 (3.3)

Table 3
An example sentence frame from Experiment 1 in five conditions. Target words are underlined for clarity.

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

and for the generation of waveform plots. No participants were removed from the final data set.

2.1.6. ERP analysis

Two separate time windows and nine electrode regions were selected for statistical analysis. The first time window of 180–220 ms covered the P200 component, and the second time window of 300–500 ms covered the N400 component. Regions of interest (ROIs; Fig. 1) used for statistical analysis were the left frontal (electrodes 25, 22, 32, 26, 23, 34, 33, 27, 24, 28, 20), mid frontal (21, 14, 15, 16, 18, 10, 19, 11, 4, 12, 5), right frontal (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 parietal (50, 51, 52, 58, 59, 60, 64, 65, 66, 69, 70), mid parietal (61, 78, 62, 67, 77, 72, 71, 76, 75, 74, 82), and right parietal (92, 85, 97, 101, 91, 84, 96, 85, 90, 95, 89) regions. For each participant and trial, the mean amplitudes for the P200 and N400 components were computed by averaging the signal amplitudes from the 11 electrodes within each ROI.

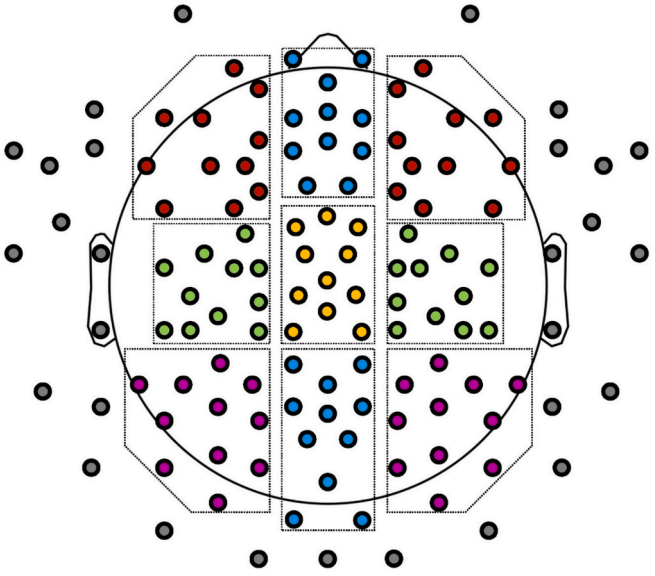


Fig. 1. ROIs for statistical analysis.

To statistically analyze the data, linear mixed-effects models (LMMs) were built using the *lme4* package (Bates et al., 2015). The mean amplitudes (calculated for the nine regions within each participant and trial) for the P200 and N400 components were used as the dependent variables in two separate LMMs for the deaf and hearing groups, respectively. Condition, hemisphere, and lobe were included as crossed fixed effects. Additionally, trial numbers (centered and scaled) were incorporated as a fixed effect to account for potential habituation effects observed over repeated trials (see Heise, Mon, & Bowman, 2022). As noted in the *Materials* section, although targets were intended to be highly predictable, not all sentence frames achieved this, resulting in variability in target predictability. To control for this variability, standardized predictability values were included as a fixed effect. Random intercepts for participants were included to account for inter-individual variability. Including items as a random effect resulted in singular fits, so it was excluded from the final models.

For each LMM, an omnibus test was performed by applying the *anova ()* function from base R to each fitted model object. The resulting ANOVA tables were used to evaluate the significance of the overall effect of condition, as well as the interaction effects of condition × hemisphere and condition × lobe. Significant results were further investigated by carrying out planned comparisons with the *emmeans* (Lenth, 2023) package, contrasting each condition (correct, orthographic, homophonic, and homovisemic) with the unrelated control condition. False discovery rate (FDR) corrections were applied separately for the four comparisons conducted within each electrode site to reduce the likelihood of Type I errors. The Satterthwaite method was used for all tests to estimate degrees of freedom and calculate *p*-values.

To conduct group comparisons, additional models were fit that included group (deaf–hearing) as a fixed effect [model structure: Amplitude ~ Group × Condition × Hemisphere × Lobe + Trial + Predictability + (1 | Participant)]. Significant interactions between group and condition; group, condition and hemisphere; and group, condition, and lobe were followed with planned comparisons.

For exploratory analyses examining the effects of reading fluency and the age of HKSL acquisition in the deaf participants, exploratory models were fit that included standardized reading fluency test scores and AoA as fixed effects [model structure: Amplitude ~ Condition × Hemisphere × Lobe × (Reading Score + AoA) + Trial + Predictability + (1 | Participant)]. The *emtrends()* function was used to check for significant relationships between contrasts and the continuous predictors of Reading Score and AoA, respectively.

To optimize statistical power by limiting the number of statistical tests, follow-up analyses for the Group comparison and exploratory models were conducted without correct–unrelated contrasts. While these contrasts might have provided some additional information, their inclusion would have necessitated a higher number of statistical tests, potentially diminishing statistical power after applying FDR

adjustments. Furthermore, the outcomes of these tests would not have directly contributed to answering the main research questions.

2.2. Experiment 1 results

2.2.1. Hearing participants

For hearing participants, the P200 window omnibus tests showed a significant condition × lobe interaction [$F(8, 31{,}823) = 2.65$, $p = .006$]. Further tests showed that P200 wave amplitudes in the orthographic and homophonic conditions were significantly reduced relative to those in the unrelated condition (orthographic: $\beta = 0.49$, $SE = 0.15$, $z = 3.21$, $p = .005$; homophonic: $\beta = 0.38$, $SE = 0.15$, $z = 2.50$, $p = .025$) across the frontal electrode sites.

In the N400 window, the overall effect of condition was significant [$F(4, 31{,}848) = 2.92$, $p = .019$], as were the condition × hemisphere [$F(8, 31{,}821) = 2.11$, $p = .031$] and condition × lobe [$F(8, 31{,}821) = 10.89$, $p < .001$] interactions. None of the pairwise tests revealed significant differences between the effects of related targets and controls within the levels of condition or the condition × hemisphere interaction. However, within the condition × lobe interaction, contrasts showed that N400 wave amplitudes were significantly more positive in the orthographic, homophonic, homovisemic, and correct conditions compared to the unrelated condition (orthographic: $\beta = 0.85$, $SE = 0.19$, $z = 4.39$, $p < .001$; homophonic: $\beta = 0.61$, $SE = 0.19$, $z = 3.14$, $p = .002$; homovisemic: $\beta = 0.50$, $SE = 0.20$, $z = 2.56$, $p = .010$; correct: $\beta = 1.09$, $SE = 0.19$, $z = 5.62$, $p < .001$) across the frontal electrode sites.

In the central lobe, N400 amplitudes were significantly more positive in the orthographic, homophonic, and correct conditions than in the unrelated condition (orthographic: $\beta = -0.57$, $SE = 0.19$, $z = -2.97$, $p = .006$; homophonic: $\beta = -0.49$, $SE = 0.19$, $z = -2.50$, $p = .017$; correct: $\beta = -0.88$, $SE = 0.19$, $z = -4.52$, $p < .001$). In the parietal lobe, orthographic and correct conditions showed significantly reduced N400s compared to the unrelated condition (orthographic: $\beta = -0.49$, $SE = 0.19$, $z = -2.52$, $p = .023$; correct: $\beta = -1.03$, $SE = 0.19$, $z = -5.31$, $p < .001$). Experiment 1 waveform plots and scalp maps for the hearing participants are presented in Fig. 2.

2.2.2. Deaf participants

Examining the deaf readers' P200 amplitudes, omnibus tests revealed a significant interaction between condition and hemisphere [$F(8, 24{,}250) = 1.99$, $p = .043$]. Further tests showed that P200 amplitudes in the left hemisphere were significantly more positive in the correct condition than in the unrelated condition ($\beta = -0.46$, $SE = 0.17$, $z = -2.63$, $p = .035$). In the middle electrode sites, P200 amplitudes were significantly more positive in both the orthographic and homophonic conditions relative to the unrelated condition (orthographic: $\beta = -0.43$, $SE = 0.17$, $z = -2.49$, $p = .035$; homophonic: $\beta = -0.41$, $SE = 0.17$, $z = -2.38$, $p = .035$).

In the N400 window, the main effect of condition was significant [$F(4, 24{,}272) = 2.41$, $p = .047$], as was the interaction between Condition and Lobe [$F(8, 24{,}251) = 11.27$, $p < .001$]. Further tests showed significantly more positive N400 amplitudes in the correct condition than in the unrelated condition across all regions ($\beta = -0.36$, $SE = 0.13$, $z = -2.76$, $p = .023$). In the central and parietal electrode sites, N400 amplitudes were significantly more positive in the orthographic condition than in the unrelated condition (orthographic, central: $\beta = -0.55$, $SE = 0.23$, $z = -2.44$, $p = .029$; orthographic, parietal: $\beta = -0.52$, $SE = 0.23$, $z = -2.31$, $p = .042$). Experiment 1 waveform plots and scalp maps for the deaf participants are presented in Fig. 3.

2.2.3. Further analysis

Interactions between condition, lobe, and reading score were significant in both the P200 and N400 windows [P200: $F(8, 24{,}163) = 5.96$, $p < .001$; N400: $F(8, 24{,}163) = 4.42$, $p < .001$]. Additional tests showed that differences in P200 wave amplitudes in the orthographic and unrelated conditions increased with reading scores at the frontal and parietal electrode sites (frontal: $\beta = -0.57$, $SE = 0.17$, $z = -3.44$, $p = .002$; parietal: $\beta = 0.49$, $SE = 0.17$, $z = 2.96$, $p = .009$), suggesting that the P200 effect of orthography is more pronounced in deaf readers with higher reading test scores. In contrast, N400 wave amplitudes in the orthographic and unrelated conditions showed significant decreases associated with higher reading scores in the same regions (frontal: $\beta = -0.84$, $SE = 0.22$, $z = -3.88$, $p < .001$; parietal: $\beta = 0.62$, $SE = 0.22$, $z = 2.88$, $p = .012$), indicating that the N400 effect of orthography is less pronounced in deaf readers with higher reading test scores. No comparable effects were found among the hearing readers ($ps > 0.1$) in either the P200 or N400 windows.

2.2.4. Group comparison

In the P200 window, omnibus tests showed significant group × condition × hemisphere [$F(8, 56{,}074) = 2.34$, $p = .02$] and group × condition × lobe interactions. Further tests showed that left hemisphere differences in P200 wave amplitudes between unrelated and orthographic conditions were significantly greater in the deaf group than in the hearing group ($\beta = -0.52$, $SE = 0.23$, $z = -2.23$, $p = .038$), while differences between unrelated and homovisemic conditions were greater in the hearing group ($\beta = -0.60$, $SE = 0.23$, $z = -2.60$, $p = .027$). Looking into the group × condition × lobe interaction, tests showed that, at the frontal electrode sites, the hearing group showed significantly greater differences between P200 wave amplitudes in the orthographic and homophonic conditions compared to the unrelated condition (orthographic: $\beta = -0.74$, $SE = 0.23$, $z = -3.21$, $p = .002$; homophonic: $\beta = -0.74$, $SE = 0.23$, $z = -3.21$, $p = .002$), while unrelated–homovisemic contrasts were significantly greater for the deaf group ($\beta = -0.48$, $SE = 0.23$, $z = -2.07$, $p = .039$). There were no significant interactions between group and condition in the N400.

2.3. Experiment 2 method

2.3.1. Sampling plan

The power analysis results for Experiment 2 showed that a sample size of 40 hearing participants would provide sufficient statistical power (approximately 80%) to detect significant interactions between condition and hemisphere, as well as condition and lobe for the P200 component.

Achieving 80% power for the overall effect of condition in the P200 and N400 windows, or for the interactions between condition and hemisphere/lobe in the N400 window, would have required a substantially larger sample size. However, the low predicted statistical power for Experiment 2 in the N400 window might be attributable to the experimental design, which aimed to elicit sign-phonological effects specifically in deaf signers. By setting the sample size at 40 hearing individuals, P200 interactions would be adequately detectable while also maintaining relatively comparable group compositions between the hearing and deaf participants. Power curve plots can be found in Fig. A2 in the appendix.

2.3.2. Participants and background measures

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

2.3.3. 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 (and was 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.

Each set belonged to one of four types of pairs: HLM pairs (see

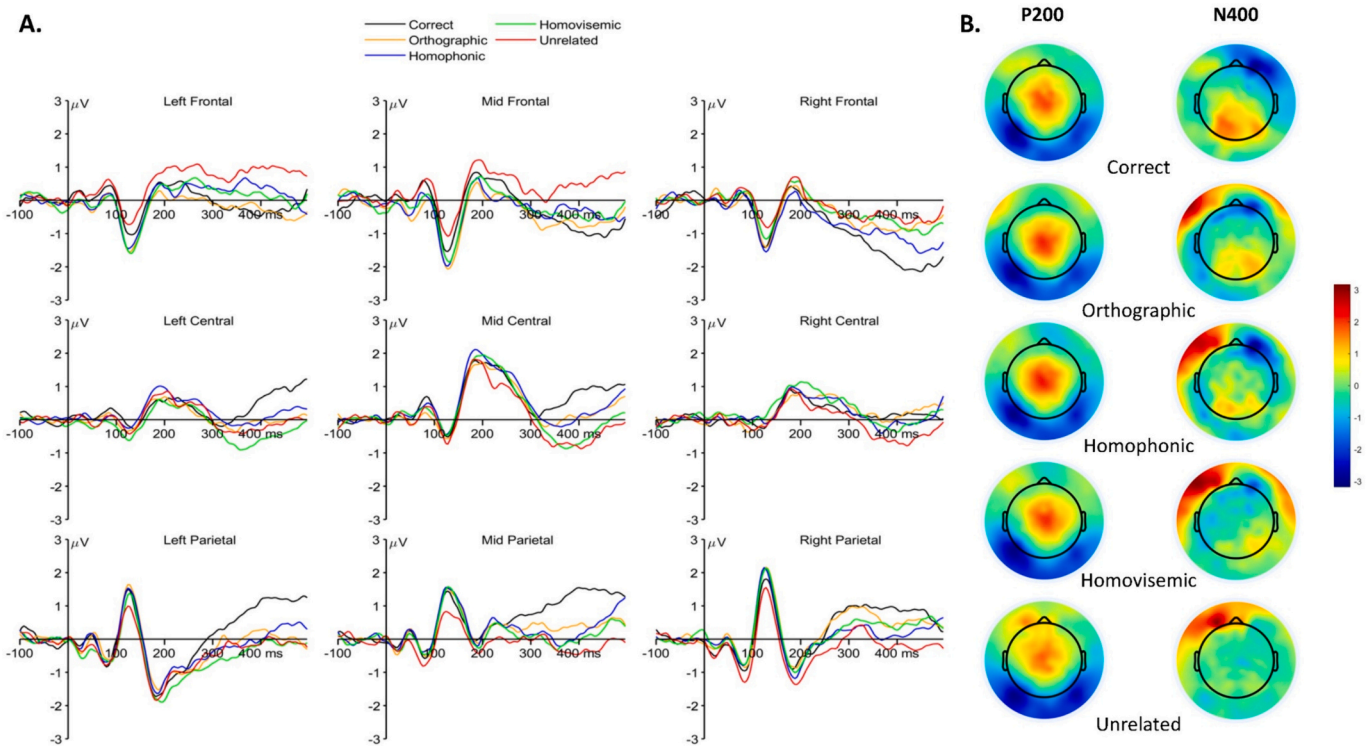


Fig. 2. Waveform plots (A) and scalp maps (B) for hearing participants in Experiment 1. Negative amplitude values are indicated on the y-axis in the downward direction. The P200 window was 180–220 ms and the N400 window was 300–500 ms.

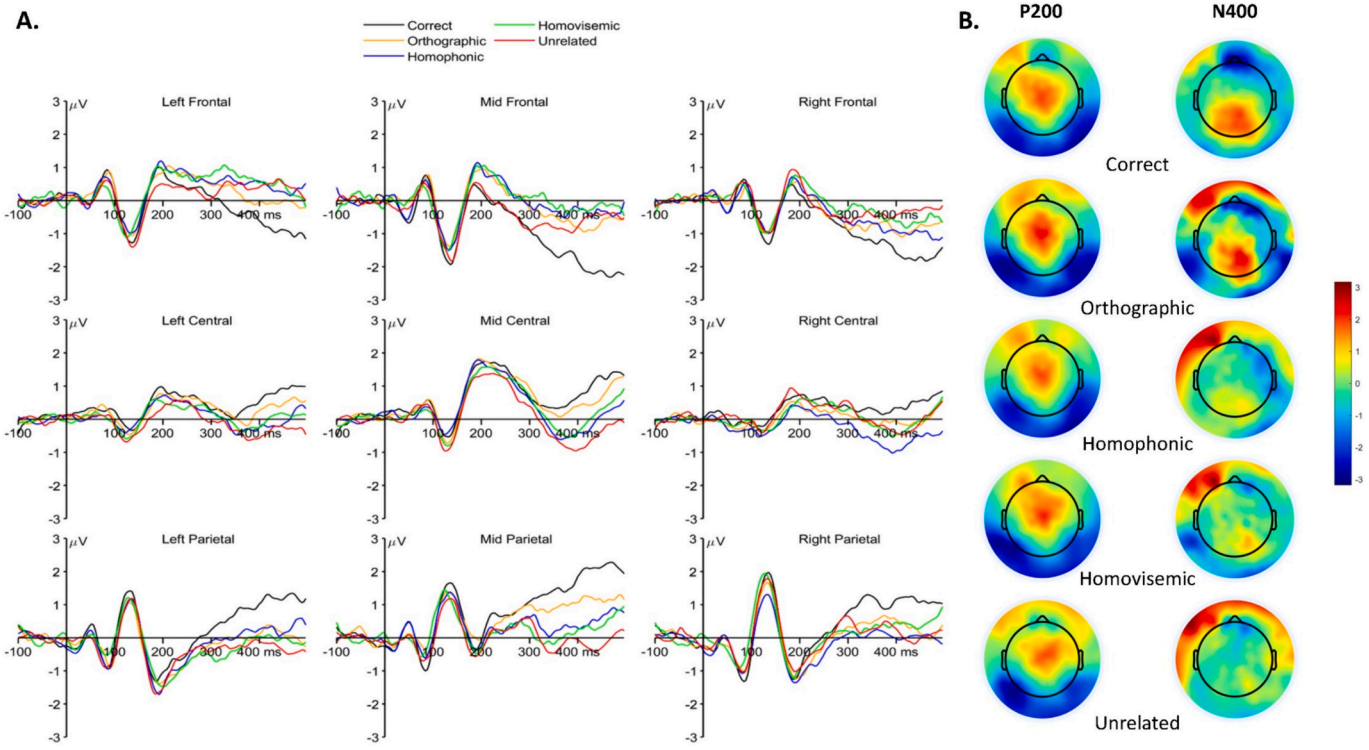


Fig. 3. Waveform plots (A) and scalp maps (B) for deaf participants in Experiment 1. Negative amplitude values are indicated on the y-axis in the downward direction. The P200 window was 180–220 ms and the N400 window was 300–500 ms.

example in Fig. 4a), which overlapped in handshape, location, and movement (note: in some cases, these differed in their non-manual features; $n = 18$); HL pairs (Fig. 4b), which overlapped in handshape and location but differed in movement ($n = 15$); HM pairs (Fig. 4c), which overlapped in handshape and movement but differed in location ($n = 17$); and LM pairs (Fig. 4d), which overlapped in location and

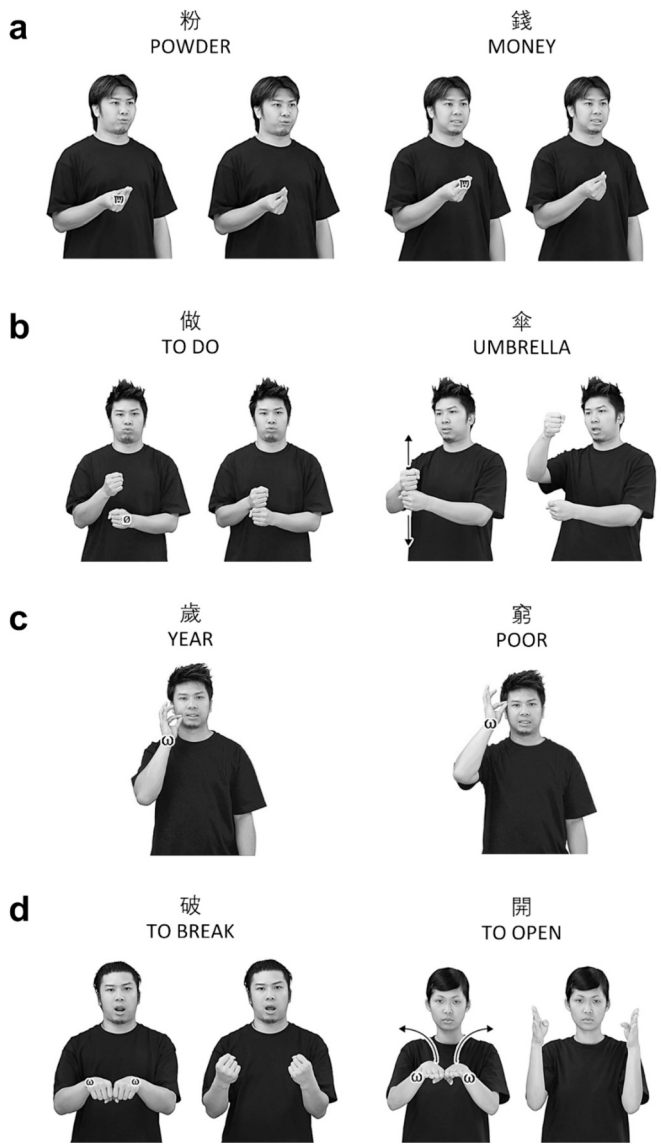


Fig. 4. Examples of sign-phonologically related translation pairs. Fig. 4a shows an example of an HLM (handshape/location/movement) sign translation pair. Fig. 4b shows an HL (handshape/location) sign translation pair. Fig. 4c shows an HM (handshape/movement) sign translation pair. Fig. 4d shows an LM (location/movement) sign translation pair. Images used with permission courtesy of the Asian SignBank (http://cslds.org/asiansignbank/).

movement but differed in handshape (n = 18). Since only a limited number of each type of pair could be found, statistical power was not high enough to examine the effects of each type individually (as was done in Thierfelder, Wigglesworth, & Tang, 2020b). Therefore, all sign-phonologically related items were treated as a single variable to look for an overall effect of sign-phonological relatedness, following the approach utilized by most previous studies on sign-phonological activation during reading (e.g., Meade et al., 2017; Morford et al., 2011; Pan et al., 2015; Villwock, Wilkinson, Piñar, & Morford, 2021).

To ensure that character pairs were not orthographically related, pairs that had overlapping semantic or phonetic radicals were avoided.[6] 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(1,102) = 1.83, p = .279]. Mean character frequencies and stroke counts did not vary significantly across conditions [Frequency: F(2,210) = 0.02, p = .985; strokes: F(2, 210) = 1.01, p = .760].

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 was a native signer of HKSL. As expected, there was a significant interaction between sub-condition and HKSL phonological similarity [F(4, 120) = 87.92, p < .001]. HLM, HL, HM, and LM pairs were rated significantly more similar than unrelated pairs (p < .001). Of the related pairs, HLM pairs were rated as the most similar (ps < 0.001). HM pairs were rated as more similar than LM pairs (p = .007). HL pairs did not differ significantly from HM pairs (p = .215) but were significantly more similar than LM pairs (p = .007). This pattern closely mirrored that found in (Thierfelder, Wigglesworth, & Tang, 2020b). Character properties are summarized in Table 4.

Each target character was embedded as the second character in a two-character word (e.g., 枱 [table] was embedded into 餐枱 [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 [meal] + [peace]) or an unrelated character in the control condition (e.g., 餐哥 [meal] + [brother]). These character pairs never constituted a legal word in Chinese.

As in Experiment 1, Experiment 2 used high-constraint sentence frames 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 one to 20 (5%–100%) per sentence, with an overall average of 75% (SD = 30%) correct guesses. In total, only eight sentences had low predictability (< 25% correct guesses). As with Experiment 1, these were retained as alternative word or sentence frames for these particular characters were unlikely to improve predictability further. As with the Experiment 1 analysis, standardized predictability values were included in the statistical models to account for possible confounding effects. Example sentences are shown in Table 5.

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.

Table 4
Experiment 2 character properties. Mean frequencies are from Ho and Kwan (2001). Semantic similarity ratings were calculated using the HowNet database (Dong et al., 2006). *SD*s are in parentheses.

	Correct	Sign-phonological	Unrelated
Frequency	121 (101)	121 (110)	123 (102)
Semantic Relatedness	–	0.20 (0.10)	0.26 (0.25)
Sign-phonological Rating	–	2.39 (1.51)	1.15 (0.48)
Stroke Count	11.5 (4.8)	11.5 (4.8)	11.0 (3.9)

[6] In 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 亻 [person] radical but had dissimilar components on the right side were retained.

Table 5
An example sentence frame from Experiment 2 in three conditions. Target words are underlined for clarity.

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

2.3.4. Procedure

Experiment 2 followed the same procedure as Experiment 1. Comprehension questions were presented after about one-fourth of the sentences to encourage participants to read for meaning. Both hearing and deaf groups were able to answer most of the questions accurately (hearing average score: $M = 81\%$, $SD = 14\%$; deaf average score: $M = 75\%$, $SD = 11\%$), but the hearing participants were significantly more accurate [$t(68) = -2.07$, $p = .042$].

2.3.5. Electroencephalography

Continuous EEG data for Experiment 2 was processed following the same procedure as Experiment 1. As with Experiment 1, epochs containing artifacts exceeding 100 μV were detected and rejected using ERPLAB's moving window peak-to-peak artifact rejection function with a window size of 100 ms and step size of 50 ms. Following this, epochs with residual voltage excursions beyond ±150 μV were identified using a simple voltage threshold method and then removed. This resulted in the discarding of an average of 9 % of trials for each hearing participant (SD = 8%) and 9 % for each deaf participant (SD = 5%). As two sign-phonologically related pairs received a mean sign-phonological similarity rating below 1.25, suggesting their perceived sign-phonological relationship was similar to character pairs in the unrelated condition, trials associated with these pairs were removed from the final dataset, resulting in a further removal of 6% of the data. No participants were removed from the final analysis.

2.3.6. ERP analysis

ERP analysis followed the same procedure as Experiment 1. However, for Experiment 2, planned comparisons contrasted the sign-phonological and correct conditions with the unrelated control condition.

2.4. Experiment 2 results

2.4.1. Hearing participants

For hearing readers, the interaction between condition and lobe was significant [$F(4, 19{,}784) = 3.13$, $p = .014$] in the P200 window, but further tests did not reveal any significant differences between the unrelated condition and sign-phonological or correct conditions.

In the N400 window, the interaction between condition and lobe was significant [$F(4, 19{,}785) = 2.74$, $p = .027$], with pairwise contrasts revealing significantly more positive N400 amplitudes in the correct condition compared to the unrelated condition in the central and parietal lobes (central: $\beta = -0.56$, $SE = 0.23$, $z = -2.41$, $p = .030$; parietal: $\beta = -0.56$, $SE = 0.23$, $z = -2.41$, $p = .040$). Experiment 2 waveform plots and scalp maps for the hearing participants are presented in Fig. 5.

2.4.2. Deaf participants

In the P200 window, the interaction between condition and lobe was significant [$F(4, 14{,}829) = 13.69$, $p < .001$]. Further tests revealed that, compared to controls, P200 amplitudes were significantly reduced in the sign-phonological condition across the frontal ($\beta = 0.59$, $SE = 0.20$, $z = -2.95$, $p = .006$) and parietal ($\beta = -0.49$, $SE = 0.20$, $z = -2.45$, $p = .018$) electrodes. In the correct condition, amplitudes were increased relative to controls at the same electrode sites (frontal: $\beta = -0.52$, $SE = 0.20$, $z = -2.59$, $p = .010$; parietal: $\beta = 0.47$, $SE = 0.20$, $z = 2.36$, $p = .018$).

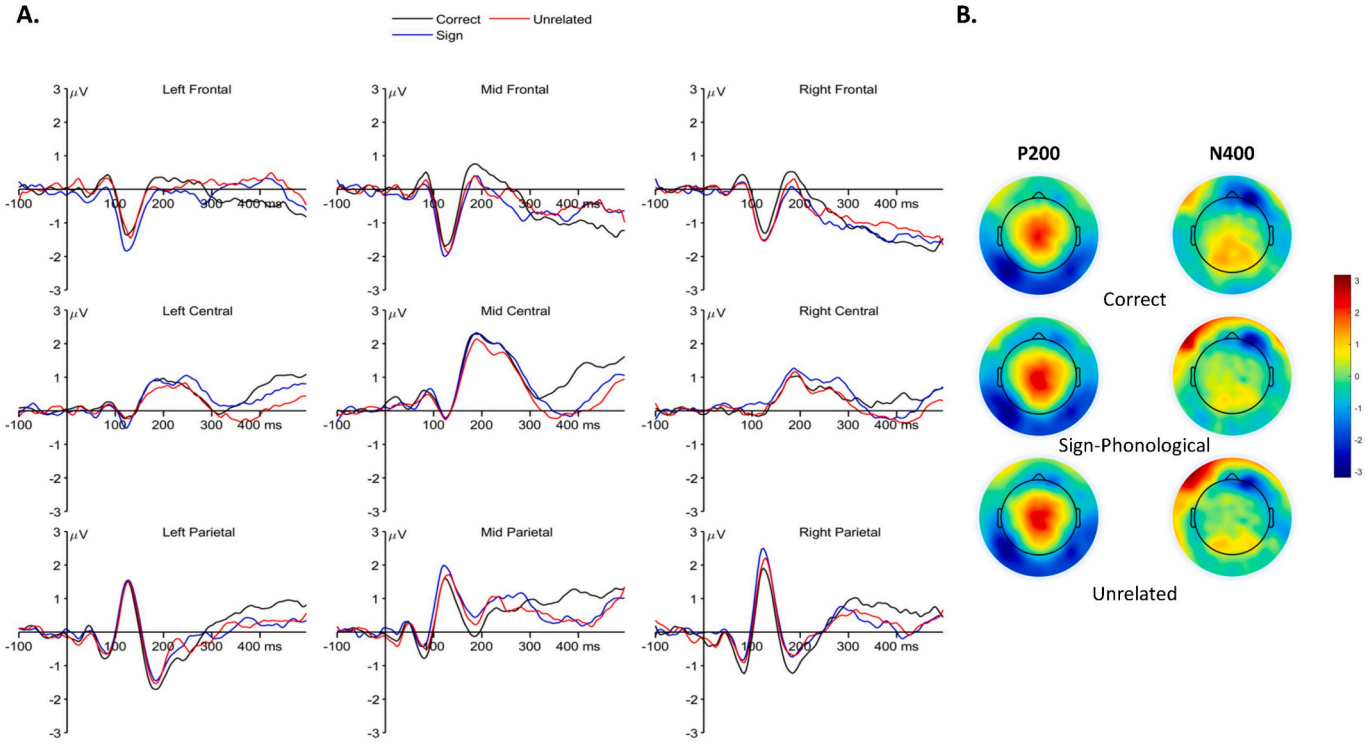


Fig. 5. Waveform plots (A) and scalp maps (B) for hearing participants in Experiment 2. Negative amplitude values are indicated on the y-axis in the downward direction. The P200 window was 180–220 ms and the N400 window was 300–500 ms.

In the N400 window, the condition × lobe interaction was significant [$F(4, 14{,}829) = 3.11$, $p = .014$]. Subsequent tests showed more negative-going wave amplitudes in the sign-phonological condition relative to the control condition in the frontal lobe ($\beta = 0.69$, $SE = 0.29$, $z = 2.41$, $p = .032$).

2.4.3. Further analysis

Looking at interactions between condition and reading score, as well as condition and AoA, found a significant interaction for condition × lobe × reading score in the N400 window [$F(4, 14{,}777) = 3.33$, $p = .009$]. However, subsequent tests did not reveal any significant effects for contrasts between the unrelated and sign-phonological conditions. Experiment 2 waveform plots and scalp maps for the deaf participants are presented in Fig. 6.

2.4.4. Group comparison

In the P200 window, the Group × Condition × Lobe was significant [$F(4, 34{,}615) = 3.78$, $p = .005$]. Further tests showed that the difference in P200 amplitudes between controls and the sign condition were significantly greater for the deaf readers than the hearing readers across the frontal electrode sites ($\beta = 0.52$, $SE = 0.26$, $z = 2.02$, $p = .043$).

There was a significant interaction between Group, Condition, and Lobe in the N400 window [$F(4, 34{,}616) = 2.51$, $p = .040$], but further tests did not show any significant differences in contrasts between the unrelated and sign-phonological conditions across between the two groups.

3. Discussion

This study aimed to investigate Cantonese and HKSL phonological activation patterns in 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 speech-based phonological processing, and included correct, orthographic, homophonic, homovisemic, and unrelated conditions. Experiment 2 focused on sign-phonological processing and included correct, sign-phonological, and unrelated conditions.

Two time windows were examined to cover the P200 (180–220 ms) and N400 (300–500 ms) components. Statistically significant differences in wave amplitudes between the unrelated condition and orthographically related condition were taken as evidence of orthographic activation. Significant differences between unrelated controls and the HKSL (i.e., sign-phonological) and Cantonese phonological (i.e., homophonic and homovisemic) conditions were taken as evidence of sign- and speech-based (or viseme-based) phonological activation, respectively. It was predicted that among the deaf participants, orthographic and sign-phonological effects would emerge early in the P200 window, and speech-based phonological effects would emerge later in the N400 window.

3.1. Hearing readers

Both experiments were carried out with a group of hearing readers, matched with the deaf group for age, education, and reading fluency, to investigate how hearing readers responded to the experimental stimuli and how these response patterns compared with those of the deaf readers. For the hearing readers, in Experiment 1, orthographic and phonological effects emerged in the P200 window and were significant at the frontal electrode sites. These findings mirror those of prior studies, showing that the P200 can be modulated by phonological (Kong et al., 2012; Liu et al., 2011; Zhang et al., 2009) and orthographic (Kong et al., 2012) information during Chinese reading.

Facilitative effects of orthography and phonology were also reflected in the N400 component. Orthographic effects were significant at the frontal, central, and parietal sites. In the homophonic condition, N400 amplitudes were more negative across the frontal electrodes and more positive across the central electrode sites. In the homovisemic condition, N400 wave amplitudes were significantly increased relative to controls at the frontal electrode sites. As most homovisemic characters overlapped with correct targets in rime, this is likely comparable to rhyming

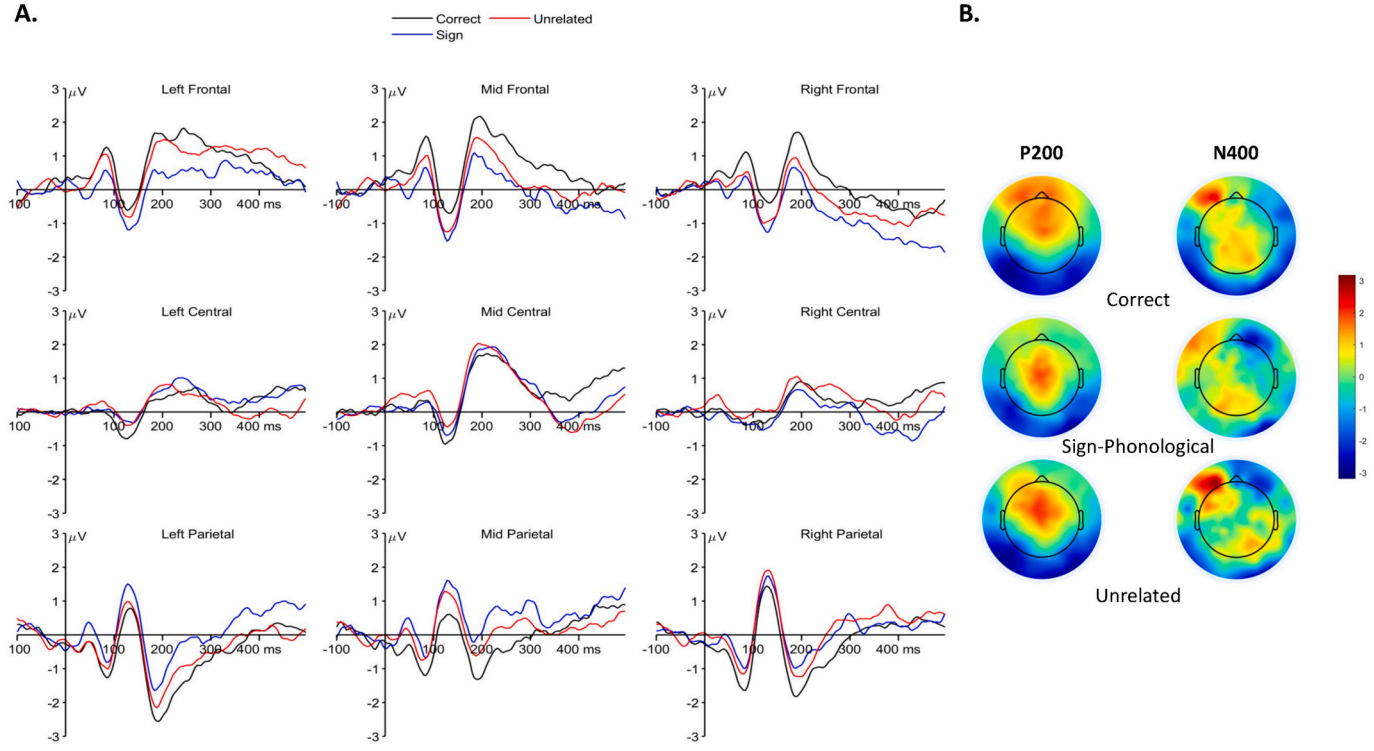


Fig. 6. Waveform plots (A) and scalp maps (B) for deaf participants in Experiment 2. Negative amplitude values are indicated on the y-axis in the downward direction. The P200 window was 180–220 ms and the N400 window was 300–500 ms.

effects found in prior ERP studies on Chinese reading (Chen et al., 2016; Kong et al., 2010). In sum, the findings of Experiment 1 suggest that the P200 and N400 windows are modulated by orthography and spoken language phonology for hearing readers during sentence reading tasks using the error disruption paradigm.

In Experiment 2, as expected, there was no effect of the sign-phonological condition in either the P200 or N400 windows for hearing readers. 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 in the deaf readers are likely to be reflecting influence from HKSL.

3.2. Deaf readers

In Experiment 1, orthographic and homophonic effects emerged in the P200 window across the middle electrode sites. Thus, as with the hearing readers, the P200 in deaf readers appears to index early orthographic and phonological activation during Chinese reading. However, for the deaf readers, these effects emerged in the middle electrode sites, rather than frontal sites as was found in the hearing readers. In the N400 window, deaf readers showed more positive N400 amplitudes in the orthographic condition across the central and parietal electrodes. There were no effects related to speech-based phonology in this window.

When the two groups in Experiment 1 were compared, orthographic effects were significantly stronger in the left hemisphere electrodes in the deaf readers, while both orthographic and homophonic conditions led to greater increases in frontal P200 amplitudes in the hearing readers. Although there were no indications of P200 homovisemic effects within either group when analyzed separately, contrasts of P200 amplitudes, comparing homovisemic characters to unrelated controls, indicated that differences between these conditions were larger for hearing readers than deaf readers in the left hemisphere, and larger for deaf readers than hearing readers in the frontal electrodes. Though this pattern does not indicate that deaf readers are relying on visemic representations in early processing (which would have been evidenced by homophonic and homovisemic conditions eliciting very similar activation patterns), it does suggest that both groups are sensitive to the phonological similarities between homovisemic and correct characters, which largely overlap in rime. No significant differences between groups were found in the N400 window for experiment 1.

In summary, during early lexical processing, deaf readers demonstrate increased sensitivity to orthographic information in the left hemisphere and homovisemic information in the frontal regions; in contrast, hearing readers show greater sensitivity to homovisemic information in the left hemisphere and orthographic and homophonic information in the frontal regions. This overall pattern may reflect the engagement of distinct neural networks by deaf and hearing readers during early orthographic and phonological processing, as evidenced by the differences in the spatial distributions of orthographic and speech-based phonological ERP effects between the two groups. These findings align with the growing body of literature proposing that deaf readers, who lack full access to speech-based phonology, develop unique cognitive mechanisms for visual-orthographic processing and word recognition (Emmorey et al., 2021; Gutierrez-Sigut et al., 2022; Thierfelder et al., 2023; Winsler, Holcomb, & Emmorey, 2023) and have altered neural connectivity in the systems underlying reading (see Emmorey & Lee, 2021).

Experiment 2 found evidence of sign-phonological activation in the P200 window across frontal and parietal electrode sites. Moreover, significant sign-phonological effects were observed at the frontal electrode sites in the N400 window. Notably, the sign-phonological condition did not elicit significant effects in the hearing group, and the interaction effects between group (deaf and hearing) and condition (sign-phonological–unrelated) reached significance at the frontal electrodes in the P200 window, indicating that the two groups exhibited differing responses to the stimuli. Taken together, these results suggest that sign-phonological activation occurs in deaf readers during the stages of early lexical access (as reflected in the P200) and semantic integration (as reflected in the N400).

One of the stated goals of this study was to better understand the time course of orthographic, speech-based phonological, and sign-phonological activation in reading among deaf bimodal bilinguals. As expected, orthographic effects were robust, emerging early in the P200 and persisting in the N400 window. Significant sign-phonological effects were also found in both these windows, while speech-based phonological effects were only found in the P200. Although it was predicted that sign-phonological activation might emerge in early processing and speech-based phonological effects may emerge later in the N400 (based on the findings of Thierfelder, Wigglesworth, & Tang, 2020a, 2020b), the current study found that both sign- and speech-based phonological effects were present in the P200 window. However, only sign-phonological effects were present across both the P200 and N400 windows. This may suggest that sign-based representations play a more sustained role across early and late stages of processing for deaf bimodal bilinguals, compared to speech-based phonological representations.

One important consideration when interpreting these results is the potential influence of the experimental paradigm used in this study. The error disruption paradigm likely led to stronger spoken language phonological activation than would occur during normal reading. When asked after the experiment, all deaf participants indicated that they had noticed the homophone manipulation in Experiment 1, but none reported noticing the sign-phonological manipulation in Experiment 2. This discrepancy likely arises because most sign-phonological pairs did not overlap on all three main sign-phonological parameters, whereas homophonic pairs always shared identical pronunciations, making the homophone manipulation more salient. Consequently, the speech-based phonological effects observed in Experiment 1, which suggested processing facilitation, might actually reflect a conscious use of phonological codes as an error-decoding strategy. This could also explain why homovisemic effects did not reach significance in either window for the deaf group—the more subtle phonological manipulation was less likely to prime deaf readers to activate spoken language phonology.

In Experiment 1, speech-based phonology showed facilitative effects, characterized by the typical pattern of an enhanced P200 and reduced N400, indicating processing facilitation. In contrast, Experiment 2, revealed a pattern of sign-phonological effects that appeared to reflect processing inhibition, as P200 and N400 amplitudes were less positive in the sign-phonological condition compared to both the unrelated and correct conditions.[7] Additionally, participants' comprehension question scores in Experiment 2 were significantly lower than those in Experiment 1 [$t(59) = 20.32$, $p = .023$]. These findings may suggest that deaf readers, aware of the Cantonese-based phonological manipulation, were able to use it to aid comprehension in Experiment 1, leading to an ERP pattern reflecting facilitation and higher comprehension question performance.

The inhibitory effect of sign-phonological activation observed in Experiment 2 can be explained by the deaf bilingual interactive activation model proposed by Ormel et al. (2012). According to this model, recognizing a written word automatically activates its sign translation and associated sign-phonological features. These activated features then spread activation to other signs sharing one or more of the same sign-phonological parameters, such as handshape, location, and movement. In the sign-phonological condition of Experiment 2, reading the sign-phonologically related character activates its meaning and sign translation, along with its sign-phonological parameters. Consequently, other signs sharing these parameters, including the sign translation of the

[7] The significant differences between the sign-phonological condition and the correct condition were confirmed by post-hoc tests (P200, Frontal and Parietal: $ps < 0.001$; N400, Frontal: $p = .008$).

correct target, are also activated. The degree of activation of the correct target's sign translation depends on the extent of its overlap with the sign-phonologically related character, with greater overlap leading to stronger activation. This process creates competition between the meanings of the related character and the correct target, resulting in processing inhibition as the reader must allocate more cognitive resources to suppress the incorrect meaning and select the correct one. The increased cognitive effort required to resolve this competition is reflected in the deaf readers' ERP data for Experiment 2, which show less pronounced P200 amplitudes and less positive N400 amplitudes in the sign-phonological condition compared to the unrelated and correct conditions. This pattern suggests that the sign-phonological manipulation interfered with lexical access and semantic integration processes, leading to the observed inhibitory effects on reading comprehension.

It is important to note that these inhibitory effects do not suggest that sign-phonological activation would negatively impact reading processes under normal circumstances. Without an experimental manipulation that induces lexical competition, these inhibitory effects would not occur in typical reading situations. Instead, these effects arise as an artifact of the experimental design, but they are informative as they suggest that sign-phonological representations are likely involved in the processes underlying reading comprehension in deaf signers.

Together, these findings support the notion that sign-phonological activation is highly automatic in deaf readers, while the activation of speech-based phonology may be more context-dependent. These observations align with the conclusions of Rowley (2018) PhD thesis, which posits that deaf readers, like their hearing counterparts, possess a flexible reading system capable of accessing meaning through multiple routes (Coltheart et al., 2001; Elliott et al., 2012; Harm & Seidenberg, 2004; Ormel et al., 2012), which allows them to utilize the information available in the text and activate speech-based phonology when the reading context facilitates or demands it.

3.3. *Deafness and reading proficiency*

According to the lexical constituency model (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 proceeds from there. The lexical quality hypothesis proposes that individuals build stronger connections between constituents through repeated exposure to words over time, resulting in the development of "high-quality" lexical representations (Perfetti, 2017; Perfetti & Hart, 2002). Sehyr and Emmorey (2022) examined the contribution of lexical quality to reading ability in deaf adults and found that it was their orthographic accuracy and semantic knowledge, rather than phonological skills, which were predictive of reading comprehension.

In the exploratory analysis, increasing reading fluency levels in deaf readers were associated with stronger orthographic effects in the P200 window and weaker orthographic effects in the N400 window. This pattern may suggest that, compared to deaf readers with lower reading proficiency, those with higher reading proficiency can more efficiently resolve orthographic errors, automatically activating and integrating target word meanings in early stages of processing. Relatedly, Thierfelder, Durantin, and Wigglesworth (2020) eye-tracking study reported that deaf readers with higher reading fluency levels were able to decipher Chinese two-character words with orthographic errors more quickly than those with lower reading fluency levels in total reading time. The results of both studies indicate that efficient orthographic processing abilities are a distinguishing feature of proficient deaf readers, enabling them to activate word meanings rapidly through direct orthographic-semantic connections. Therefore, developing lexical representations with robust connections between orthographic and semantic representations may be crucial for the acquisition of skilled reading in deaf individuals (as discussed in Bélanger et al., 2013; Emmorey & Lee, 2021; Sehyr & Emmorey, 2022; and Thierfelder et al., 2023, among others).

4. Limitations and conclusion

Before concluding, it is important to acknowledge that power analyses indicated that the sample sizes used in this study were likely not large enough to consistently detect all significant effects and interactions in both groups, suggesting an increased likelihood of Type II errors (false negatives). Future research, perhaps in areas with larger communities of deaf signers, could aim to replicate these findings with larger sample sizes to ensure adequate power for detecting all relevant effects and interactions. Employing alternative experimental paradigms using more subtle speech-based phonological manipulations may also be useful for better understanding the degree of automaticity in deaf readers' activation of speech-based phonology.

In conclusion, the primary aim of this study was to investigate the patterns of speech-based phonological and sign-phonological activation in deaf readers. In line with the models proposed by Elliott et al. (2012) and Thierfelder, Wigglesworth, and Tang (2020a), our findings indicate that deaf readers are capable of accessing word meanings through either a direct orthographic-semantic route or an indirect route mediated by speech- or sign-based phonology. Notably, deaf readers who exhibited higher levels of reading fluency demonstrated more pronounced orthographic effects in the early stages of processing compared to their less fluent peers. This underscores the importance of strong orthographic-semantic connections for the development of proficient reading skills among deaf individuals.

Furthermore, this study highlighted similarities between sign-phonological processing in deaf readers and speech-based phonological processing in hearing readers. In both groups, phonological activation influenced both early lexical access and later semantic integration, as evidenced by the P200 and N400 effects. Although the spatial topographies of these effects varied, significant involvement of frontal regions was observed for both sign- and speech-based phonological activation effects among deaf and hearing readers, respectively. These parallels lend support to the hypothesis proposed by Petitto et al. (2016), which is that sign language phonology plays a similar role in the reading processes of deaf readers as spoken language phonology does in hearing readers.

The implications of these findings are relevant to teaching practices in deaf education. Firstly, they suggest that instruction in a natural sign language can serve as a bridge between orthography and meaning for developing deaf readers, just as spoken language can for developing hearing readers. Furthermore, by strengthening the links between orthography and meaning in deaf reading instruction through a rich linguistic environment and frequent engagement with text, educators can leverage the unique cognitive strengths of deaf individuals to potentially enhance academic outcomes.

CRediT authorship contribution statement

Philip Thierfelder: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Data availability

Data and scripts are publicly available on the Open Science Framework (https://osf.io/yk935/).

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Appendix

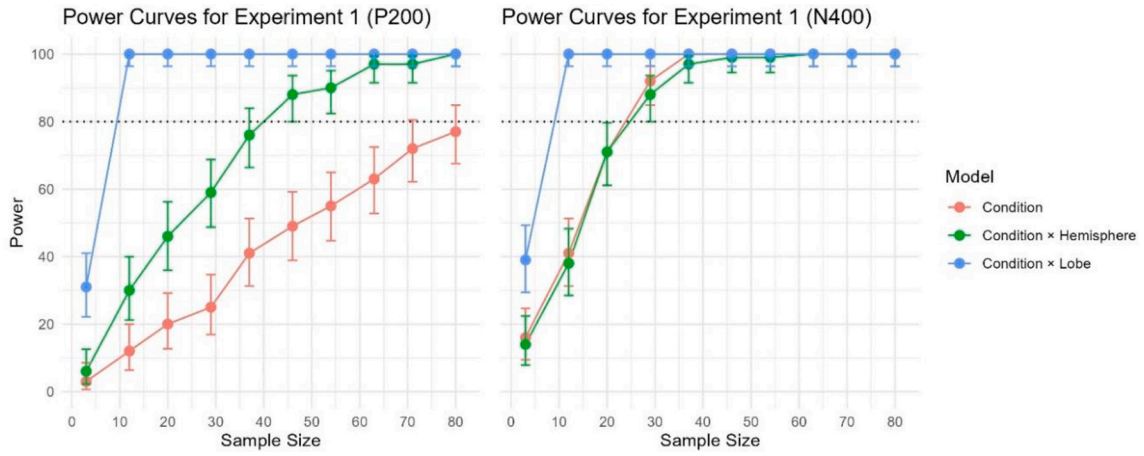


Fig. A1. Power curve plots for Experiment 1.

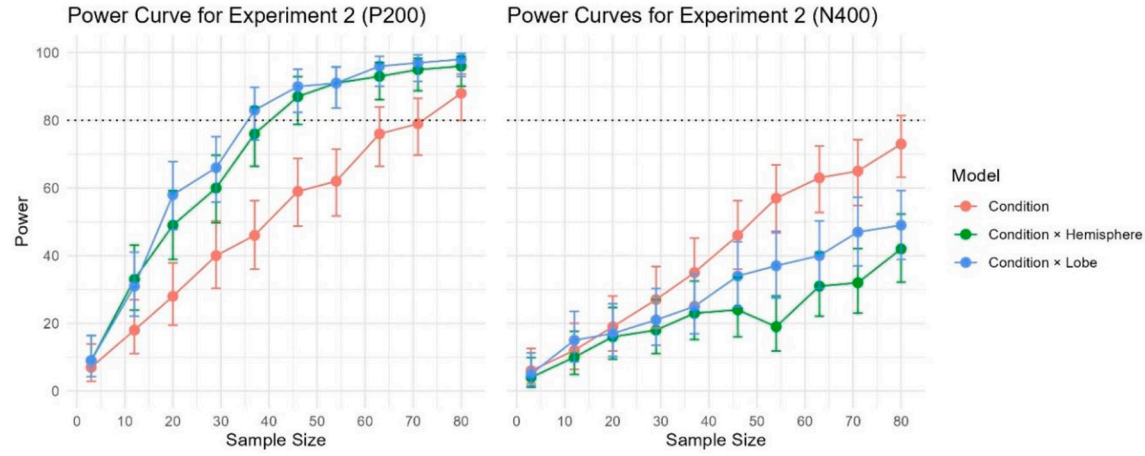


Fig. A2. Power curve plots for Experiment 2.

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