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Phonological and orthographic processing during second language typing production of Chinese-English bilinguals

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ABSTRACT

Two basic issues in written production concern whether phonology influences the output of orthography and how language processes affect the motor execution. Previous studies conducted in the native language (L1) have provided evidence for handwriting production, but less is known about how phonology and orthography work in second language (L2) typing production, and whether their work would be modulated by L2 proficiency. In the current study, the picture-word interference paradigm was adopted, in which 45 proficient (Experiment 1) and 44 non-proficient (Experiment 2) Chinese-English bilinguals were required to typewrite the English name of the picture while attempting to ignore written distractor word. The distractor word was either orthographically highly related (near-bear), phonologically highly related (chair-bear), or unrelated (cloud-bear) to the picture name (e.g., bear). The response times for the cognitive coding phase, as well as the whole response duration and the mean length of inter-keystroke intervals for the motor execution phase, were recorded. The overall results suggested that phonological and orthographic processing in the two phases might be modulated by L2 proficiency, which may be due to the differences in the quality and accessibility of phonological and orthographic representations for bilinguals with different L2 proficiency. Finally, we conducted Experiment 3 to test our interpretation.

1. Introduction

There is a consensus that written production comprises a cognitive coding phase, during which the orthographic representation is accessed from semantics, and a motor execution phase, in which the writing movements are implemented (Ellis, 1988; Hulstijn & van Galen, 1988). Is a phonological mediator required for semantic access to orthographic representation in the cognitive coding phase? Does linguistic information in the cognitive coding phase influence the motor execution phase? These are the two fundamental issues in the field of written production over the years (Cerni & Job, 2022; Damian & Qu, 2013; Lambert & Quémart, 2019; Qu et al., 2011; Wang et al., 2012).

For the first issue on the phonological role during orthography access, debates have led to the *phonological mediation hypothesis* and the *orthographic autonomy hypothesis*. According to the *phonological mediation hypothesis*, access to orthography is possible only via prior retrieval of phonological codes. In other words, semantics activate phonological representation necessarily before orthographic one (Bonin et al., 2001; Damian et al., 2011; Qu et al., 2015). This view is consistent with the fact that spoken language precedes written production ontogenetically and phylogenetically. Comparable impairments in spoken and written production exhibited by neuropsychological patients (Basso et al., 1978), the common introspective experience of writing achieved (Hotopf, 1980), spelling errors in homophone substitution (Aitchison & Todd, 1982), and higher spelling errors generated by brain-impaired patients in sound-to-print inconsistency (Bonin et al., 2001) consistently provide early evidence for the phonological mediation hypothesis. In recent years, this hypothesis has also received empirical support with the classical picture-word interference (PWI) paradigm. This paradigm consists of two essential variables: the types of distractor words and the stimulus onset asynchrony (SOA) between the presentation of the picture and the distractor. Based on the fact that reading is

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faster than naming (Fraisse, 1969), the automatic activation of reading distractor words in the picture-word interference paradigm can compete with picture naming within a certain range of temporal proximity for interference to occur (Glaser & Düngelhoff, 1984). Does an earlier (negative SOA), a slightly later (positive SOA), or an exactly synchronous (0 ms for SOA) distractor word yield the strongest effects on picture naming? The main idea is to isolate temporal and functional aspects of context effects by separating temporally the onset of the two stimulus components with adequate controls, yielding time course functions for the effects of distractors on target processing that allow some precise inferences about the underlying cognitive processing (Dyer, 1971; Glaser & Düngelhoff, 1984; Posner & Snyder, 1975; Schriefers et al., 1990; Taylor, 1977). By manipulating SOA, it is allowed to tap into successive stages of word processing as a writing response is being prepared. For example, Zhang and Damian (2010) employed PWI to examine the role of phonology during orthographic access of handwriting with native English speakers. Distractor words were either orthographically and phonologically related (OP), orthographically related only (O), or unrelated to the picture name. As the phonological mediation hypothesis predicted, it was found that phonological facilitation (SOA = 0 ms) emerged earlier than orthographic one (SOA = 100 ms). Applying the same paradigm, Qu et al. (2011) examined the phonological contribution during orthographic access of handwriting with native Chinese speakers. Distractor words were either orthographically and phonologically related (OP), phonologically related only (P), or unrelated to the picture name. Similarly, results showed that phonology (SOA = 0 ms) was accessed earlier than orthography (SOA = 100 ms), which was in line with the phonological mediation hypothesis. Nevertheless, the above studies have two potential limitations: First, the negative SOA was not considered. Commonly, the appearance of the distractor word precedes the picture when SOA is negative, in this case, the former has more time to complete its own activation process, making it easier to impact the subsequent target naming processing. It seems to occur due to involuntary activation of parts of the target's cognitive pathway by the distractor, as well as due to voluntarily formed expectations or directed attention. This effect can be understood as a response priming that helps subjects prepare for subsequent responses (Glaser & Glaser, 1982; Neely, 1977; Posner & Snyder, 1975; Taylor, 1977). Specifically, if the distractor word presented in advance plays a positive priming on subsequent picture naming, it will facilitate the performance; otherwise, it will interfere with the following picture naming. Given that two studies reached their conclusion of phonological mediation based on the findings at the SOA of 0 ms, could orthographic effects occur exclusively at a negative SOA? Second, the P-related condition was not included in Zhang and Damian (2010), as well as the O-related condition was not included in Qu et al. (2011), which led to the P effect or O effect being inferred by comparing the OP effect with the O effect, or OP effect with the P effect, respectively, which may have a potential impact on their conclusions (Zhang & Wang, 2015). Contrary to the former hypothesis, the *orthographic autonomy hypothesis* assumes that individuals can gain access to orthographic representation directly from semantics without phonological mediation. That is, orthography can be activated before or at the same time as phonology (Bonin et al., 1998; Rapp et al., 1997; Shen et al., 2013). Studies on brain-impaired patients have provided early evidence for this view (Alario et al., 2003; Miceli et al., 1997). Importantly, this hypothesis has received experimental evidence of native Chinese handwriting with more rigorous manipulation of PWI (Zhang & Wang, 2015). In this study, researchers modified the PWI by including a negative SOA (−100 ms), and the distractor words of O-related and P-related. Results found that the orthographic priming effect (SOA = −100 ms) arises earlier than the phonological one (SOA = 100 ms). This finding suggests that semantics can access the orthographic representation directly in Chinese writing, supporting the orthographic autonomy hypothesis.

Despite extensive research on the phonological role of orthographic access during written production, it was mainly focused on handwriting, while typing was neglected. Previous studies revealed that typing involves separate cognitive processes from handwriting (Lyu et al., 2021). Mangen and Velay (2010) identified four primary differences between these two modes. First, handwriting is an unimanual activity associated with the brain's lateralization for language and motor functions, while typing requires bimanual activity and may engage inter-hemispheric processing. Second, compared to handwriting, it takes less time to produce the same word by typing, which may not be conducive to the retention of words in writers' brains due to the shorter processing time (Gentner, 1983). Third, handwriting facilitates cognitive processing by linking the focus of sensory-motor actions and visual output tightly on a tiny area of the paper and the tip of the pen, whereas typing possibly reduces cognitive intensity due to the distracted attention between the keyboard (the motor space) and screen (the visual space) (Higashiyama et al., 2015; Mangen et al., 2015). Fourth, unlike handwriting, which processes the shape and position of individual letters in a word, typing only involves dealing with the position of letters in a word, which may not be beneficial to memorizing graphic forms (Naka & Naoi, 1995). In addition, peripheral processes regarding motor actions for producing letters/words of handwriting require both allographic/letter-shape conversion and graphic-motor planning, whereas typing requires graphic-motor planning only (Purcell et al., 2011; Rumelhart & Norman, 1982; Salthouse, 1986; Teulings et al., 1983; van Galen et al., 1989; Wu & Liu, 2008). Moreover, fMRI studies found that both handwriting and typing activated the left anterior superior parietal lobule (associated with visuospatial processing), the left supramarginal gyrus (associated with motor representations), and the posterior end of the left middle frontal gyrus/superior frontal gyrus (associated with spatially oriented working memory) while typing primarily activated the left posteromedial intraparietal cortex, which is involved in spelling knowledge (Buchwald & Rapp, 2009; Higashiyama et al., 2015). It may be that more working load is needed and thus there were higher orthographic working memory demands in typing than in handwriting (Higashiyama et al., 2015). Above all, studies from psychology and neuroscience have consistently indicated that typing and handwriting involve distinct cognitive processes, which may influence the mechanism of orthographic access in two writing modes. However, it is under-explored whether a phonological mediator is required during orthographic access when typing.

Regarding the process of typing production, researchers have further divided it into the cognitive coding phase and the motor execution phase. The former refers to the process of extracting orthographic representation from long-term memory, which is generally measured by response times (RTs, the time taken to press the first key). The latter refers to the process of translating the orthographic representation into hand and finger motor commands and executing the typing movements, which is commonly measured by whole response duration (WRD, the time elapsed between the first and the last key press of the word) and inter-keystroke intervals (IKIs, the time elapsing between two key presses) (Afonso et al., 2015; Damian & Stadthagen-Gonzalez, 2009; Kandel et al., 2013; Lambert & Quémart, 2019). For the second issue about the influence of language information on the motor execution phase, a *serial model* postulates that linguistic processes involved in the construction of the orthographic representation do not affect typing execution, being terminated before this execution. This view aligns with the research findings that language processes affect RTs but do not affect WRD or IKIs. For example, in a Stoop color-word task, Logan and Zbrodoff (1998) found that the typical Stoop effect interfered with typing RTs but had no effect on WRD, which was repeated in Damian and Freeman (2008). Similarly, Baus et al. (2013) found an effect of lexical frequency on typing RTs, but without any effect on WRD and IKIs. These findings suggest that motor execution is separated from earlier linguistic processes, which is consistent with the serial model. However, a *cascade model* assumes linguistic processes can spread into the motor execution phase as they are still active (Cerni & Job, 2022; van Galen, 1990). This is supported by previous findings about the significant influence of language processes on WRD or IKIs. For instance, Gentner et al. (1988) found that infrequent bigrams and the presence of a syllable boundary could cascade into the typing execution and slow down IKIs. Furthermore, in a picture typing task, Scaltritti et al. (2016) found that lexical frequency and name agreement could affect not only RTs but also IKIs. Despite the above evidence of linguistic effects on motor execution, research about the influence of phonology and orthography on motor execution is very scarce.

Current knowledge about the above two issues comes mainly from studies on native language (L1), however, far too little attention has been paid to the second language (L2) —which focuses more on the co-activation and inhibition of non-target languages during bilingual written production with alphabetic languages (Iniesta et al., 2021; Muscalu & Smiley, 2019; Wong & Maurer, 2021) —especially for the question whether L2 written processing is potentially affected by L1 writing experience in the case of the two languages characterized by substantial differences in writing systems, for example, Chinese-English. Specifically, the Chinese writing system possesses numerous unique characteristics that distinguish it from alphabetic systems, manifested in several aspects such as its logographic nature, various strokes and radicals, visual and spatial complexity, and uncertain phonetic relations. First of all, the Chinese character writing system is primarily logographic, meaning that each character represents a morpheme or a word. Unlike alphabetic systems where letters represent phonemes, Chinese characters convey meaning directly through their visual forms, which allows for the representation of complex concepts in a single character. In addition, Chinese characters are composed of various strokes and multiple radicals, and their complex combinations and intricate structures require more visual and spatial attention to the placement and proportion of each component, which makes learning and mastering the Chinese writing system a significant challenge. Furthermore, Chinese phonology includes pervasive homophones—each spoken syllable corresponds to approximately 11 characters—which makes it typically ambiguous for the representation of a spoken word/syllable to a single character in terms of its meaning. For Chinese-English bilinguals, given English (L2) structure of orthographic systems is significantly different from Chinese (L1) and begins to be learned later, would its written production be influenced by the Chinese writing experience? Perfetti et al. (2007) proposed an *assimilation and accommodation hypothesis* based on how the brain comes to support the acquisition of a new writing system. The *assimilation hypothesis* assumes that bilinguals adopt L1 strategies to process L2, showing that the neural pattern of L2 processing is similar to that of L1. In contrast, the *accommodation hypothesis* postulates that bilinguals apply L2 strategies to process L2, showing that the neural pattern of L2 processing is similar to that of L2 as the native language. Previous studies suggest that for Chinese-English bilinguals, their neural networks of phonological processing between L1 and L2 were quite similar, and they tend to apply L1 assimilation mechanisms for L2 phonological processing (Gao & Zhang, 2005; Tan et al., 2003). Therefore, there may be an orthographic autonomous path in L2 typing, similar to L1 handwriting, as the cognitive coding processes are assumed to be common to handwriting and typing (Cerni & Job, 2022). Furthermore, studies from behavior (Costa & Santesteban, 2004; Fan et al., 2012; Ye et al., 2011), EEG (Botezatu, 2023; Xue & Cui, 2024), and fMRI (Abutalebi et al., 2013; Grant et al., 2015; Sun et al., 2019) have consistently showed that L2 proficiency seems to be one of the most relevant factors for predicting bilingual performance of language processing, which governing the representation of L2 in the brain (Perani et al., 1998). Given L2 proficiency's essential role in language processing, how would it modulate the phonological and orthographic processing during L2 typing production? For the first issue on the phonological role during orthography access, given that proficient bilinguals' L2 phonological awareness is higher with years of L2 education than that of non-proficient bilinguals (Gao & Zhang, 2005), would the phonological role in proficient bilinguals be stronger than non-proficient ones? For the second issue about the influence of language information on motor execution, according to the proposition of Bosga-Stork et al. (2016), once writing motor execution has reached a certain level of development, it seems to become an autonomous system, relatively independent of the cognitive coding system; that is to say, linguistic processes may affect writing movements, but only until motor execution acquires relative independence from other linguistic systems (Afonso et al., 2018). Given that proficient bilinguals' level of L2 motor execution is higher than that of non-proficient bilinguals, would the proficient bilinguals' motor execution be independent of the linguistic system and support the serial model, while non-proficient bilinguals' motor execution be influenced by linguistic processing and consistent with the cascade model?

Based on the studies mentioned above, the current study focused on the following questions: (a) Does phonology influence the output of orthography in the cognitive coding phase during L2 typing production? (b) How do L2 phonological and orthographic processing affect motor execution? (c) Are the findings of the above two questions modulated by L2 proficiency? For question (a), previous research generally determined the activation of phonology or orthography by comparing phonologically related condition with the unrelated condition, as well as orthographically related condition with the unrelated condition, at each SOA in the phase of cognitive coding; and then determined to support the phonological mediation or orthographic autonomy hypothesis by comparing the earliest SOA of phonological activation with that of orthographic activation (Qu et al., 2011; Zhang & Damian, 2010; Zhang & Wang, 2015). For question (b), whether phonology and orthography were activated at different SOAs in the motor execution phase was also an important issue that we focused on. Therefore, planned comparisons *t*-tests need to be conducted to investigate the phonological and orthographic effects at each SOA in the phases of cognitive encoding and motor execution, as this is the main interest of the present study (Wong & Maurer, 2021). For question (c), both proficient and non-proficient Chinese-English bilinguals were recruited to explore the potential modulation of L2 proficiency.

Given that phonological and orthographic codes for English as an alphabetic language are interrelated closely, it is challenging to separate one from another completely. To ensure a minimum overlap on grapheme between phonologically related distractor and the picture name, as well as phoneme between orthographically related distractor and the picture name, we innovatively utilized the presence of polyvalent grapheme (one phonological representation with two orthographic specifications, e.g. /eə(r)/ for both "air" in the chair and "ear" in the bear) and polyvalent phoneme (one orthographic representation with two phonological specifications, e.g. ear for both /iə(r)/ in the near and /eə(r)/ in the bear) in English. This novel approach allowed us to create phonologically highly related (i.e., the correlation degree of the distractor word and the picture name on phonological level is significantly higher than that on orthographic level) (e.g., *chair-bear*) and orthographically highly related (i.e., the correlation degree of the distractor word and the picture name on orthographic level is significantly higher than that on phonological level) (e.g., *near-bear*) distractor conditions. Additionally, we introduced negative SOAs to explore the earlier effects of phonology and orthography during typing production.

To our knowledge, little research has combined the cognitive coding phase with the motor execution phase to investigate phonological and orthographic processing during Chinese-English bilinguals' L2 typing production, much less the potential moderating effect of L2 proficiency. Specifically, two hypotheses were proposed. First, the role of L2 phonology on orthographic access in the cognitive coding phase was examined. Previous studies suggest that for Chinese-English bilinguals, their neural networks of phonological processing between L1 and L2 were quite similar, and they tend to apply L1 assimilation mechanisms for L2 phonological processing (Gao & Zhang, 2005; Tan et al., 2003). Therefore, we predicted an orthographic autonomous path in L2 typing, similar to L1 handwriting, as the cognitive coding processes are assumed to be common to handwriting and typing (Cerni & Job, 2022). It is noteworthy that proficient bilinguals' L2 phonological awareness is higher with years of L2 education than that of non-proficient bilinguals (Gao & Zhang, 2005), we hypothesized that the phonological role in proficient bilinguals may be stronger than non-proficient ones. Second, the influence of phonological and orthographic processing on the motor execution phase was explored. According to the proposition of Bosga-Stork et al. (2016), once writing motor execution has reached a certain level of development, it seems to become an autonomous system, relatively independent of the cognitive coding system; that is to say, linguistic processes may affect writing movements, but only until motor execution acquires relative independence from other linguistic systems (Afonso et al., 2018). Given proficient bilinguals' level of L2 motor execution is higher than that of non-proficient bilinguals, we expected that proficient bilinguals' motor execution would be independent of the linguistic system and support the serial model, while non-proficient bilinguals' motor execution would be influenced by linguistic processing and consistent with the cascade model.

In this article, we report an extensive investigation of phonological and orthographic processing during L2 typing production of Chinese-English bilinguals. The current study is organized into three experiments. First, we adopted the PWI paradigm to investigate the L2 phonological and orthographic processing in proficient bilinguals (Experiment 1). Next, we investigated the same question in non-proficient bilinguals (Experiment 2). The results of the two experiments suggest that L2 proficiency might modulate the processing of phonology and orthography in the different phases of typing production, which may be due to the differences in the quality and accessibility of phonological and orthographic representations during motor execution for bilinguals with different L2 proficiency. Finally, we conducted Experiment 3 to test our interpretation.

2. Experiment 1

2.1. Participants

We used G*Power software (version 3.1.9) to calculate the sample size. According to our experimental design, a sample size of 24 participants was needed to detect an effect size of 0.25 (power = 0.8, α = 0.05). These parameters are based on the G*Power manual. In the current study, 45 proficient Chinese-English bilingual students (22 males and 23 females, age $M = 21.80$, $SD = 0.87$) majoring in English who had passed the TEM-4 (Test for English Majors Band 4), were paid to participate in the study. TEM-4 is a test designed for students in English major. Only students who major in English are qualified to take part in this exam at colleges and universities in China. It consisted of six parts: dictation, listening comprehension, integration testing, reading comprehension, essay writing, and oral test. Since the TEM-4 exam was complicated, those who passed the TEM-4 were considered highly proficient in English. Based on the flexibility of Language History Questionnaire (LHQ 3.0; Li et al., 2020) and our focus, we used Questions 5 and 11 to collect bilinguals' AoA, years of use, and proficiency of their two languages (Question 5: *Indicate your native language and any other languages you have studied or learned, the age at which you started using each language in terms of listening, speaking, reading, and writing, and the total number of years you have spent using each language.* Question 11: *Rate your current ability in terms of listening, speaking, reading, and writing in each of the languages you have studied or learned.*).The questionnaire showed that they were native Chinese speakers with English as their L2, and the mean age of acquisition (AoA) for English was 9.93 ($SD = 0.33$), and their years of use, as well as proficiency in English, were less than Chinese ($ps<0.001$) (Table 1). All were right-handed with normal or corrected-to-normal vision and signed a written informed consent form before the experiment. The experiment had been approved by the ethical committee of the local authority.

2.2. Materials and design

The target pictures were twenty white-line drawings on a black background, of which eighteen were selected from Zhang and Yang's (2003) picture database, and the other two were self-selected by the researcher. Thirty non-English major college students who passed CET-6 (College English Test Band 6, the passing of which equals the medium level in English) were asked to evaluate the pictures using a 5-point scale, including the familiarity, name consistency, and visual complexity of the pictures. According to the evaluation results, there were no significant differences in familiarity, name consistency, and visual complexity between the two self-selected pictures and the eighteen ones in the database ($ps > 0.05$). For English, due to the difficulty of completely separating its orthography and phonology, we adopted the criteria used by Lupker (1982), specifically, the relationship between orthographically highly related (O) distractor words and picture names must meet the following criteria: ① their spellings are identical except for the first letter; and ② their single vowel sounds are different in their standard pronunciations; any phonological similarity is limited to the last phoneme (e.g., the picture name *bear*/beə(r)/, and the orthographic related distractor *near*/nɪə(r)/). Phonologically highly related distractor (P) and picture names must meet the following criteria: ① the two words rhyme in the sense that other than the initial phoneme, they are identically pronounced; ②the words have the same letter in no more than one other position (e.g., the picture name is *bear*, and the phonological related distractor word is *chair*/tʃeə(r)/). For unrelated distractor words, the associative picture-distractor relationships on orthography, phonology, or semantics should be avoided (e.g., the picture name *bear*/beə(r)/ and the unrelated distractor *cloud*). The length of all distractor words was controlled between 3 and 6 letters, and there was no significant difference in the word frequency ($ps > 0.05$).

Trials were blocked by SOA and the order of SOA blocks for each participant was determined by a Latin square design. Each block included twenty formal pictures, three practice pictures, and ten filler pictures. Each formal picture is presented with 3 types of distractor words, respectively, with a new pseudorandom order of the constraint that no pictures were repeated on consecutive trials. The practice and filler pictures were all accompanied by an unrelated distractor word. A complete list of experimental materials is presented in the Appendix A.

The experiment conforms to a 5 (SOA: −200 ms, −100 ms, 0 ms, 100 ms, and 200 ms) × 3 (Distractor Type: orthographically highly related, phonologically highly related, and unrelated) within-subjects design, with the reaction times (RTs) in the phase of cognitive coding, as well as the whole response duration (WRD) and the mean inter-keystroke intervals (IKIs) in the phase of motor execution, as the dependent variables.

Table 1
Language history questionnaire of proficient bilinguals.

Aspects	L1 (Chinese)				L2 (English)			
	Listening	Speaking	Reading	Writing	Listening	Speaking	Reading	Writing
Age of Acquisition (Q.5)	1.00 ± 0.00	1.47 ± 0.50	3.96 ± 0.71	4.40 ± 0.50	9.93 ± 0.33	9.93 ± 0.33	9.93 ± 0.33	9.93 ± 0.33
Years of Use (Q.5)	21.80 ± 0.87				11.87 ± 1.01			
Proficiency (Q.11)	6.87 ± 0.34	6.84 ± 0.37	6.93 ± 0.25	6.80 ± 0.40	5.27 ± 0.45	5.53 ± 0.50	6.31 ± 0.51	5.54 ± 0.53

2.3. Procedure

The experiment was performed using *E*-Prime software (version 2.0). The participants were tested individually. They were first asked to familiarize themselves with the experimental stimuli by viewing each picture for 3000 ms with the picture name on the computer screen. Then, five experimental blocks of 70 trials each were presented. Every trial began with a fixation cross presented at the center of the screen for 500 ms, followed by a blank screen for 500 ms, and then target pictures and distractor words were presented at the appropriate time according to different SOA. Specifically, for SOA = −200 ms and − 100 ms, the distractor word preceded the target picture for 200 ms or 100 ms; for SOA = 0 ms, the distractor and target appeared simultaneously; for SOA = 100 ms and 200 ms, the distractor appeared later than the target picture for 100 ms or 200 ms.

The distractor words were presented centrally and superimposed on the target pictures. The participants were asked to press the space bar rapidly (the pictures and distractors disappear simultaneously) and typewrite down the picture name as quickly and accurately as possible while attempting to ignore the distractor words. The trial finished when the participants pressed the space bar again. There was then a black inter-trial screen for 1000 ms. For the cognitive encoding phase, one dependent variable was recorded: the reaction times (RTs) from the onset of the picture to the first space bar keypress. For the motor execution phase, another two dependent variables were recorded: 2) the whole response duration (WRD) from the first keystroke to the second space bar keypress and 3) the inter-keystroke intervals (IKIs) for the time elapsing between two key presses.

2.4. Results

RTs for correct naming trials shorter than 200 ms and longer than 2000 ms (4.3 %) were excluded from the analysis, and a secondary trimming step was used to exclude naming latencies over 2.5 standard deviations (*SDs*) above or below the mean of each condition (3.0 %). The mean response times and accuracy of each condition in the cognitive coding phase of proficient bilinguals are shown in Table 2.

Linear Mixed-effects Models with the lme4 and the lmerTest packages (Kuznetsova et al., 2017) performed in R (version 4.0.2) were used to analyze the results, which included fixed effects of distractor type (orthographically highly related, phonologically highly related, unrelated), and SOA (−200 ms, −100 ms, 0 ms, 100 ms, 200 ms) and by-participant and by-item random intercepts. Models were fit to the data using a restricted maximum likelihood technique. Model fitting was carried out by initially specifying a model that only included the random factors (participants and items), which was then enriched by subsequently adding the fixed factor distractor type, followed by SOA, and finally, the interaction between the two factors. The best-fitting model was defined as the most complex model that significantly improved the fit over the previous model.

Table 2
Mean RTs and ACC of proficient bilinguals ($M \pm SD$).

SOA	Distractor Type	RTs (ms)	ACC
SOA = -200 ms	orthographically highly related (O)	668 ± 211	0.97 ± 0.18
	phonologically highly related (P)	676 ± 206	0.95 ± 0.21
	unrelated (U)	695 ± 221	0.97 ± 0.16
SOA = -100 ms	orthographically highly related (O)	658 ± 205	0.95 ± 0.21
	phonologically highly related (P)	676 ± 209	0.97 ± 0.16
	unrelated (U)	690 ± 213	0.98 ± 0.15
SOA = 0 ms	orthographically highly related (O)	674 ± 217	0.97 ± 0.17
	phonologically highly related (P)	691 ± 228	0.96 ± 0.20
	unrelated (U)	708 ± 236	0.96 ± 0.19
SOA = 100 ms	orthographically highly related (O)	579 ± 225	0.96 ± 0.20
	phonologically highly related (P)	582 ± 229	0.96 ± 0.20
	unrelated (U)	597 ± 242	0.96 ± 0.20
SOA = 200 ms	orthographically highly related (O)	513 ± 224	0.96 ± 0.20
	phonologically highly related (P)	523 ± 217	0.96 ± 0.20
	unrelated (U)	520 ± 235	0.95 ± 0.21

2.4.1. Reaction times (RTs)

The best-fitting model included both distractor type and SOA as main effects, $\chi^2_{(1,\ N=12,081)} = 20.98$,[1] $p<0.001$. Including the interaction between SOA and distractor type did not improve the fit, $\chi^2 = 6.34$, $p = 0.610$. Planned comparisons with Bonferroni correction assessed the effects of distractor types at each SOA separately and showed that at the SOA of −200 ms, the O condition was significantly faster than the unrelated condition (diff = 27 ms: 668 ms vs. 695 ms, β = −34.12, $t(1673) = -4.84$, $p<0.001$), and the P condition was significantly faster than the unrelated condition (diff = 19 ms: 676 ms vs. 695 ms, β = −22.60, $t(1643) = -3.18$, $p = 0.005$); at the SOA of −100 ms, the O condition was significantly faster than the unrelated condition (diff = 32 ms: 658 ms vs. 690 ms, β = −30.10, $t(1672) = -4.61$, $p<0.001$); at the SOA of 0 ms, the O condition was significantly faster than the unrelated condition (diff = 34 ms: 674 ms vs. 708 ms, β = −35.25, $t(1674) = -4.81$, $p<0.001$), and the P condition was significantly faster than the unrelated condition(diff = 17 ms: 691 ms vs. 708 ms, β = −18.61, $t(1666) = -2.53$, $p = 0.034$); at the SOA of 100 ms, the O condition was significantly faster than the unrelated condition (diff = 18 ms: 579 ms vs. 597 ms, β = −22.23, $t(1608) = -3.01$, $p = 0.008$), and the P condition was significantly faster than the unrelated condition(diff = 15 ms: 582 ms vs. 597 ms, β = −19.11, $t(1601) = -2.58$, $p = 0.030$); at the SOA of 200 ms, none of the effects were significant ($ps>0.246$). (see Table 3). Based on previous research, we determined the earliest O effect and P effect by comparing the SOAs of their first occurrence (Qu et al., 2011; Zhang & Damian, 2010; Zhang & Wang, 2015). The results indicate that the earliest effects of both O and P occurred at the SOA of −200 ms, providing strong evidence for the simultaneous activation of orthography and phonology.

Table 3
Planned comparisons at each SOA of RTs for proficient bilinguals.

Fixed effect	β	SE	t	p
Unrelated condition as reference				
SOA = -200 ms				
(Intercept)	707.87	26.09	27.14	<0.001
Orthographically highly related (O)	−34.12	7.05	−4.84	<0.001
Phonologically highly related (P)	−22.60	7.12	−3.18	0.005
SOA = -100 ms				
(Intercept)	695.23	26.17	26.57	<0.001
Orthographically highly related (O)	−30.10	6.53	−4.61	<0.001
Phonologically highly related (P)	−12.28	6.51	−1.89	0.177
SOA = 0 ms				
(Intercept)	715.80	27.65	25.89	<0.001
Orthographically highly related (O)	−35.25	7.34	−4.81	<0.001
Phonologically highly related (P)	−18.61	7.36	−2.53	0.034
SOA = 100 ms				
(Intercept)	603.29	30.39	19.85	<0.001
Orthographically highly related(O)	−22.23	7.38	−3.01	0.008
Phonologically highly related (P)	−19.11	7.40	−2.58	0.030
SOA = 200 ms				
(Intercept)	511.74	25.88	19.78	<0.001
Orthographically highly related (O)	−15.94	9.16	−1.74	0.246
Phonologically highly related (P)	1.65	9.10	0.18	0.999

[1] Here and in the results reported thereafter, N indicates the number of observations which was included in the model.

2.4.2. Whole response duration(WRD)

The mean WRD of each condition in the motor execution phase is shown in Table 4.

The best-fitting model included both distractor type and SOA, $\chi^2_{(1, N=12,081)} = 68.70$, $p<0.001$. Including the interaction between SOA and distractor type did not improve the fit, $\chi^2 = 9.00$, $p = 0.342$. Planned comparisons with Bonferroni correction showed that the P condition was significantly faster than the unrelated condition at the SOA of 0 ms (diff = 36 ms: 1552 ms vs. 1588 ms, $\beta = -39.71$, $t(1666) = -2.53$, $p = 0.035$). There were no significant effects at other SOAs ($ps>0.250$) (see Table 5).

2.4.3. Inter-keystroke intervals(IKIs)

The mean IKIs of each condition in the motor execution phase are shown in Table 2. The best-fitting model included both distractor types and SOA, $\chi^2_{(1,\ N=12,081)} = 33.86$, $p<0.001$. Adding the interaction between distractor type and SOA did not significantly improve the fit, $\chi^2 = 4.65$, $p = 0.795$. Planned comparisons with Bonferroni correction showed no significant effects of distractor types at any SOAs ($ps>0.117$) (see Table 6).

2.5. Discussion

The results of Experiment 1 showed that in the cognitive coding phase, both orthographic and phonological priming effects emerged initially at the SOA of −200 ms. This result suggests that for proficient bilinguals, the activation of L2 orthographic representation can be as rapid as that of phonological representation. Therefore, the result pattern aligns with the orthographic autonomy view, which posits that orthography can be activated directly from semantics, bypassing the need for phonological mediation. Furthermore, we observed that in the motor execution phase, phonology facilitated the WRD at the SOA of 0 ms, while neither phonology nor orthography affected IKIs at any SOA. This result indicates that for proficient bilinguals, the processing of L2 phonology can cascade into the motor execution phase and promote the whole response duration. In contrast, orthographic processing has been terminated before motor execution.

3. Experiment 2

3.1. Participants

44 non-proficient Chinese-English bilingual students (22 males and 22 females, age $M = 20.30$, $SD = 0.79$) from non-English majors who had not passed CET-4 (College English Test-4) yet were paid to participate in the experiment. The CET-4 was a standardized basic exam of English at colleges and universities in China, which was mandatory for students in China who were not English majors. It contained four parts:

Table 4
Mean WRD and IKIs of proficient bilinguals ($M \pm SD$).

SOA	Distractor Type	WRD (ms)	IKIs (ms)
SOA = -200 ms	Orthographically highly related (O)	1551 ± 485	837 ± 346
	Phonologically highly related (P)	1549 ± 473	831 ± 328
	Unrelated (U)	1561 ± 494	823 ± 341
SOA = -100 ms	Orthographically highly related (O)	1545 ± 448	822 ± 338
	Phonologically highly related (P)	1572 ± 471	824 ± 338
	Unrelated (U)	1549 ± 458	827 ± 331
SOA = 0 ms	Orthographically highly related (O)	1567 ± 501	834 ± 350
	Phonologically highly related (P)	1552 ± 502	822 ± 349
	Unrelated (U)	1588 ± 508	813 ± 313
SOA = 100 ms	Orthographically highly related (O)	1602 ± 529	857 ± 364
	Phonologically highly related (P)	1619 ± 523	857 ± 349
	Unrelated (U)	1621 ± 506	847 ± 336
SOA = 200 ms	Orthographically highly related (O)	1618 ± 495	869 ± 341
	Phonologically highly related (P)	1616 ± 538	860 ± 363
	Unrelated (U)	1607 ± 515	853 ± 349

Table 5
Planned comparisons at each SOA of WRD for proficient bilinguals.

Fixed effect	β	SE	t	p
Unrelated condition as reference				
SOA = -200 ms				
(Intercept)	1572.14	67.23	23.39	<0.001
Orthographically highly related (O)	−16.60	15.91	−1.04	0.891
Phonologically highly related (P)	−18.89	16.05	−1.18	0.718
SOA = -100 ms				
(Intercept)	1548.44	64.88	23.87	<0.001
Orthographically highly related (O)	−4.68	14.99	−0.31	0.999
Phonologically highly related (P)	25.91	14.95	1.73	0.250
SOA = 0 ms				
(Intercept)	1594.69	72.38	22.03	<0.001
Orthographically highly related (O)	−20.94	15.66	−1.34	0.544
Phonologically highly related (P)	−39.71	15.70	−2.53	0.035
SOA = 100 ms				
(Intercept)	1622.05	72.47	22.38	<0.001
Orthographically highly related(O)	−21.12	15.95	−1.32	0.557
Phonologically highly related (P)	−5.41	15.99	−0.34	0.999
SOA = 200 ms				
(Intercept)	1608.61	74.69	21.54	<0.001
Orthographically highly related (O)	−0.91	16.55	−0.06	0.999
Phonologically highly related (P)	13.39	16.45	0.81	0.999

Table 6
Planned comparisons at each SOA of IKIs for proficient bilinguals.

Fixed effect	β	SE	t	p
Unrelated condition as reference				
SOA = -200 ms				
(Intercept)	831.82	52.60	15.82	<0.001
Orthographically highly related (O)	7.78	10.80	0.72	0.999
Phonologically highly related (P)	0.35	10.90	0.03	0.999
SOA = -100 ms				
(Intercept)	825.77	53.56	15.42	<0.001
Orthographically highly related (O)	−3.92	10.45	−0.38	0.999
Phonologically highly related (P)	1.22	10.42	0.12	0.999
SOA = 0 ms				
(Intercept)	817.76	54.43	15.03	<0.001
Orthographically highly related (O)	21.72	10.53	2.06	0.117
Phonologically highly related (P)	5.39	10.55	0.51	0.999
SOA = 100 ms				
(Intercept)	845.89	54.30	15.58	<0.001
Orthographically highly related(O)	8.11	11.05	0.73	0.999
Phonologically highly related (P)	6.11	11.08	0.55	0.999
SOA = 200 ms				
(Intercept)	849.04	54.78	15.50	<0.001
Orthographically highly related (O)	7.87	12.03	0.65	0.999
Phonologically highly related (P)	14.13	11.95	1.18	0.712

reading comprehension, listening comprehension, integration testing, and essay writing. Since the CET-4 exam was more accessible than the TEM-4 exam, those who failed the CET-4 were considered lowly proficient in English. Previous studies have used CET and TEM tests to distinguish between different levels of English proficiency (Cheng, 2008; Yan & Yang, 2006; Sun et al., 2019; Ren, 2011). All participants completed Questions 5 and 11 in LHQ 3.0. The questionnaire showed that they were native Chinese speakers with English as their L2, the mean AoA for English was 10.07($SD = 0.45$), and their years of use, as well as proficiency in English, were less than Chinese ($ps<0.001$) (Table 7). All were right-handed with normal or corrected-to-normal vision and signed a written informed consent form before the

Table 7
Language history questionnaire of non-proficient bilinguals.

Aspects	L1 (Chinese)				L2 (English)			
	Listening	Speaking	Reading	Writing	Listening	Speaking	Reading	Writing
Age of Acquisition (Q.5)	1.00 ± 0.00	1.61 ± 0.49	3.93 ± 0.76	4.41 ± 0.50	10.07 ± 0.45	10.07 ± 0.45	10.07 ± 0.45	10.07 ± 0.45
Years of Use (Q.5)	20.30 ± 0.79				10.23 ± 0.86			
Proficiency (Q.11)	6.91 ± 0.29	6.89 ± 0.32	6.93 ± 0.25	6.70 ± 0.46	3.05 ± 0.43	3.09 ± 0.47	4.57 ± 0.55	4.25 ± 0.49

experiment. In addition, the *t*-test showed L2 proficiency of proficient bilinguals was higher than that of non-proficient ones ($p<0.001$), but no differences in Raven test scores (proficient group: $M = 100.50$, $SD = 13.23$; non-proficient group: $M = 100.00$, $SD = 15.00$), $t(87) = 0.17$, $p = 0.866$, as well as typing speed (proficient group: $M = 48.00$, $SD = 9.22$; non-proficient group: $M = 46.00$, $SD = 8.76$, $t(87) = 1.05$, $p = 0.298$).

3.2. Materials, design, and procedure

The materials, design, and procedure used in Experiment 2 were the same as in Experiment 1.

3.3. Results

RTs for correct naming trials shorter than 200 ms and longer than 2000 ms (6.91 %) were excluded from the analysis, and a secondary trimming step was used to exclude naming latencies over 2.5*SDs* above or below the mean of each condition (2.83 %). The mean response times and accuracy of each condition in the cognitive coding phase for non-proficient bilinguals are shown in Table 8.

3.3.1. Reaction times (RTs)

The best-fitting model included both distractor type and SOA, $\chi^2_{(1, N=11,425)} = 15.06$, $p<0.001$. Adding the interaction between distractor type and SOA did not significantly improve the fit, $\chi^2 = 11.88$, $p = 0.157$. Planned comparisons with Bonferroni correction assessed the effects of distractor types at each SOA separately and showed that at the SOA of −200 ms, the O condition was significantly faster than the unrelated condition (diff = 28 ms: 682 ms vs. 710 ms, $\beta = -32.28$, $t(1588) = -3.99$, $p<0.001$); at the SOA of 0 ms, the O condition was significantly faster than the unrelated condition (diff = 40 ms: 678 ms vs. 718 ms, $\beta = -41.89$, $t(1586) = -4.90$, $p<0.001$), and the P condition was significantly faster than the unrelated condition(diff = 29 ms: 689 ms vs. 718 ms, $\beta = -28.88$, $t(1594) = -3.38$, $p = 0.002$); at the SOA of 100 ms, the O condition was significantly faster than the unrelated condition (diff = 35 ms: 618 ms vs. 653 ms, $\beta = -33.80$, $t(1512) = -3.49$, $p = 0.002$), and the P condition was significantly faster than the unrelated condition(diff = 38 ms: 615 ms vs. 653 ms, $\beta = -32.45$, $t(1507) = -3.34$, $p = 0.003$); at the SOA of 200 ms, no effects were significant (*ps*>0.999) (see Table 9).

Table 8
Mean RTs and ACC of non-proficient bilinguals (*M* ± *SD*).

SOA	Distractor Type	RTs (ms)	ACC
SOA = -200 ms	Orthographically highly related (O)	682 ± 239	0.96 ± 0.19
	Phonologically highly related (P)	694 ± 251	0.96 ± 0.18
	Unrelated (U)	710 ± 252	0.96 ± 0.20
SOA = -100 ms	Orthographically highly related (O)	691 ± 272	0.96 ± 0.19
	Phonologically highly related (P)	694 ± 263	0.96 ± 0.18
	Unrelated (U)	706 ± 278	0.96 ± 0.20
SOA = 0 ms	Orthographically highly related (O)	678 ± 265	0.97 ± 0.18
	Phonologically highly related (P)	689 ± 276	0.96 ± 0.19
	Unrelated (U)	718 ± 291	0.96 ± 0.20
SOA = 100 ms	Orthographically highly related (O)	618 ± 282	0.97 ± 0.16
	Phonologically highly related (P)	615 ± 285	0.96 ± 0.20
	Unrelated (U)	653 ± 304	0.94 ± 0.24
SOA = 200 ms	Orthographically highly related (O)	547 ± 270	0.95 ± 0.21
	Phonologically highly related (P)	544 ± 255	0.96 ± 0.19
	Unrelated (U)	554 ± 266	0.96 ± 0.20

Table 9
Planned comparisons at each SOA of RTs for non-proficient bilinguals.

Fixed effect	β	SE	t	p
Unrelated condition as reference				
SOA = -200 ms				
(Intercept)	725.42	31.75	22.85	<0.001
Orthographically highly related (O)	−32.28	8.10	−3.99	<0.001
Phonologically highly related (P)	−15.07	8.12	−1.86	0.191
SOA = -100 ms				
(Intercept)	728.66	35.29	20.65	<0.001
orthographically highly related (O)	−16.00	8.27	−1.94	0.159
phonologically highly related (P)	−16.17	8.22	−1.97	0.148
SOA = 0 ms				
(Intercept)	738.58	35.79	20.64	<0.001
Orthographically highly related (O)	−41.89	8.56	−4.90	<0.001
Phonologically highly related (P)	−28.88	8.53	−3.38	0.002
SOA = 100 ms				
(Intercept)	653.49	37.10	17.62	<0.001
Orthographically highly related(O)	-33.80	9.70	−3.49	0.002
Phonologically highly related (P)	-32.45	9.71	−3.34	0.003
SOA = 200 ms				
(Intercept)	537.90	32.24	16.69	<0.001
Orthographically highly related (O)	−5.01	10.88	−0.46	0.999
Phonologically highly related (P)	−6.34	10.86	−0.58	0.999

Above all, the results showed that the earliest O effect occurred at the SOA of −200 ms while the earliest P effect was at the SOA of 0 ms, indicating that orthography was activated earlier than phonology.

3.3.2. Whole response duration(WRD)

The mean WRD of each condition in the motor execution phase for non-proficient bilinguals is shown in Table 10.

The best fitting model included distractor type, SOA, and their interaction, $\chi^2_{(1, N=11,425)} = 14.63$, $p = 0.067$. Planned comparisons with Bonferroni correction showed that at the SOA of −200 ms, the O condition was significantly faster than the unrelated condition (diff = 48 ms: 1969 ms vs. 2017 ms, $\beta = -61.54$, $t(1588) = -2.48$, $p = 0.039$); at the SOA of 100 ms, the P condition was significantly slower than the unrelated condition (diff = 57 ms: 1957 ms vs. 1900 ms, $\beta = 57.81$, $t(1507) = 2.55$, $p = 0.033$). There were no significant effects at other SOAs (*ps*>0.098) (see Table 11).

3.3.3. Inter-keystroke intervals (IKIs)

The mean IKIs of each condition in the motor execution phase for non-proficient bilinguals are shown in Table 4. The best fitting model included both distractor type and SOA, $\chi^2_{(1, N=11,425)} = 16.29$, $p = 0.003$. Adding the interaction between distractor type and SOA did not significantly improve the fit, $\chi^2 = 12.17$, $p = 0.144$. Planned comparisons with Bonferroni correction showed that at the SOA of −100 ms, the P condition was significantly slower than the unrelated condition (diff = 55 ms: 1122 ms vs. 1067 ms, $\beta = 53.43$, $t(1588) = 2.92$, $p = 0.011$). There were no significant effects at other SOAs (*ps*>0.190) (see Table 12).

Table 10
Mean WRD and IKIs of non-proficient bilinguals ($M \pm SD$).

SOA	Distractor Type	WRD (ms)	IKIs (ms)
SOA = -200 ms	Orthographically highly related (O)	1969 ± 745	1069 ± 519
	Phonologically highly related (P)	1970 ± 752	1061 ± 538
	Unrelated (U)	2017 ± 850	1075 ± 531
SOA = -100 ms	Orthographically highly related (O)	2017 ± 819	1097 ± 565
	Phonologically highly related (P)	2040 ± 790	1122 ± 584
	Unrelated (U)	1984 ± 767	1067 ± 530
SOA = 0 ms	Orthographically highly related (O)	1922 ± 707	1041 ± 481
	Phonologically highly related (P)	1976 ± 1027	1077 ± 695
	Unrelated (U)	1973 ± 729	1063 ± 498
SOA = 100 ms	Orthographically highly related (O)	1934 ± 725	1075 ± 539
	Phonologically highly related (P)	1957 ± 749	1069 ± 537
	Unrelated (U)	1900 ± 684	1038 ± 484
SOA = 200 ms	Orthographically highly related (O)	1981 ± 781	1099 ± 543
	Phonologically highly related (P)	1992 ± 796	1094 ± 562
	Unrelated (U)	1961 ± 779	1084 ± 541

3.4. Discussion

The results of Experiment 2 showed that in the cognitive coding phase, the orthographic priming effect first occurred at the SOA of −200 ms, while the phonological priming effect was observed at the SOA of 0 ms. This result suggests that for non-proficient bilinguals, the activation of L2 orthography precedes that of phonology. The result pattern is in line with the orthographic autonomy view, indicating that orthography can be activated directly from semantics without phonological mediation. In the motor execution phase, we found that L2 orthography shortened the WRD at the SOA of −200 ms, while phonology prolonged the IKIs at the SOA of −100 ms, and eventually delayed the WRD at the SOA of 100 ms. This finding implies that for non-proficient bilinguals, both orthography and phonology processing can cascade into the motor execution phase.

Furthermore, since the two experiments were completely identical in design, materials, and procedures, with only the proficiency differing, to more directly compare the differences in phonological and orthographic processing during L2 typing production between proficient and non-proficient bilinguals, we also conducted a combined ANOVA analysis based on the mixed design of 2(Proficiency: proficient bilinguals, non-proficient bilinguals) × 5 (SOA: −200 ms, −100 ms, 0 ms, 100 ms, and 200 ms) × 3 (Distractor Type: orthographically highly related, phonologically highly related, and unrelated), with the RTs in the cognitive coding phase, as well as the WRD and IKIs in the motor execution phase, as the dependent variables. Geisser-Greenhouse corrections were reported where applicable.

Analysis of the RTs showed that the three-way interaction was insignificant, $F(8, 645) = 1.09$, $p = 0.361$. Based on the previous studies (e.g., Damian & Qu, 2013, Exp. 1 & 2; Kingsley et al., 2017; Jandhyala, 2015; Zhang & Damian, 2010, Exp.2), planned comparisons were conducted and showed that for proficient bilinguals, at the SOA of −200 ms, the O condition was significantly faster than the unrelated condition, $p<0.001$, and the P condition was significantly faster than the unrelated condition, $p = 0.002$; at the SOA of −100 ms, the O condition was significantly faster than the unrelated condition, $p<0.001$; at the SOA of 0 ms, the O condition was significantly faster than the unrelated condition, $p = 0.001$; there were no significant effects at other SOAs (Fig. 1, left). For non-proficient bilinguals, at the SOA of −200 ms, the O condition was significantly faster than the unrelated condition, $p = 0.001$; at

Table 11
Planned comparisons at each SOA of WRD for non-proficient bilinguals.

Fixed effect	β	SE	t	p
Unrelated condition as reference				
SOA = -200 ms				
(intercept)	2032.79	111.15	18.29	<0.001
orthographically highly related (O)	−61.54	24.80	−2.48	0.039
phonologically highly related (P)	−47.94	24.87	−1.93	0.162
SOA = -100 ms				
(Intercept)	1988.94	113.55	17.52	<0.001
Orthographically highly related (O)	27.50	24.90	1.10	0.808
Phonologically highly related (P)	52.94	24.75	2.14	0.098
SOA = 0 ms				
(Intercept)	1978.25	112.11	17.65	<0.001
Orthographically highly related (O)	−53.41	28.73	−1.86	0.189
Phonologically highly related (P)	−2.80	28.64	−0.10	0.999
SOA = 100 ms				
(Intercept)	1904.61	104.31	18.26	<0.001
Orthographically highly related(O)	22.68	22.68	1.00	0.953
Phonologically highly related (P)	57.81	22.70	2.55	0.033
SOA = 200 ms				
(Intercept)	1971.21	109.97	17.93	<0.001
Orthographically highly related (O)	8.85	26.31	0.34	0.999
Phonologically highly related (P)	25.03	26.26	0.95	0.999

Table 12
Planned comparisons at each SOA of IKIs for non-proficient bilinguals.

Fixed effect	β	SE	t	p
Unrelated condition as reference				
SOA = -200 ms				
(Intercept)	1089.72	81.91	13.30	<0.001
Orthographically highly related (O)	−16.11	16.87	−0.96	0.999
Phonologically highly related (P)	−18.02	16.92	−1.07	0.861
SOA = -100 ms				
(Intercept)	1075.60	84.22	12.77	<0.001
Orthographically highly related (O)	24.88	18.43	1.35	0.532
Phonologically highly related (P)	53.43	18.32	2.92	0.011
SOA = 0 ms				
(Intercept)	1072.47	82.06	13.07	<0.001
Orthographically highly related (O)	−23.04	19.78	−1.17	0.733
Phonologically highly related (P)	11.92	19.72	0.60	0.999
SOA = 100 ms				
(Intercept)	1039.35	79.98	13.00	<0.001
Orthographically highly related (O)	29.48	16.96	1.74	0.247
Phonologically highly related (P)	31.53	16.97	1.86	0.190
SOA = 200 ms				
(Intercept)	1077.86	82.10	13.13	<0.001
Orthographically highly related (O)	3.87	19.24	0.20	0.999
Phonologically highly related (P)	9.75	19.20	0.51	0.999

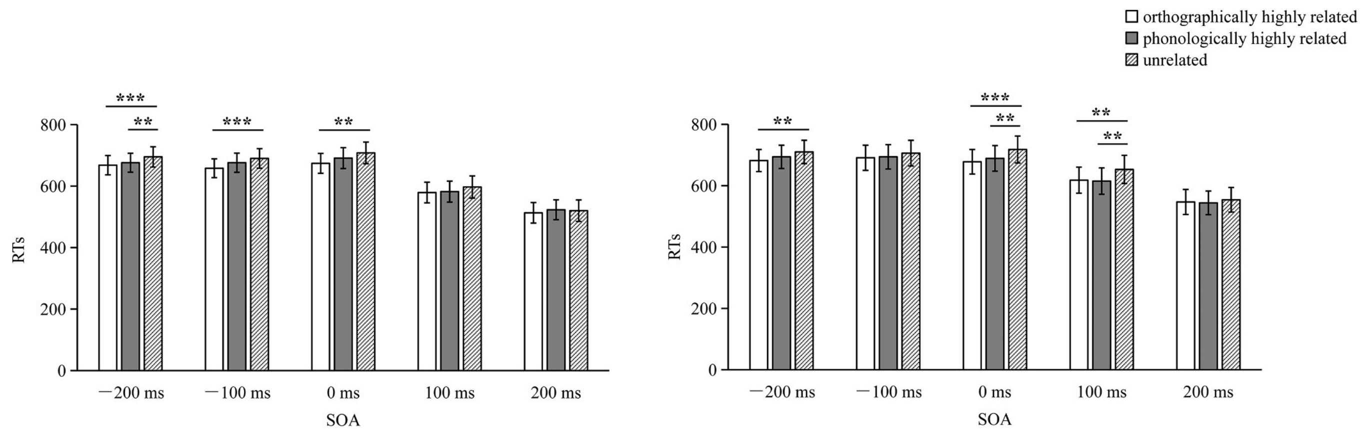

Fig. 1. RTs at each SOA of proficient bilinguals (left) and non-proficient bilinguals (right) (Error bars reflect standard errors of the mean, *$p<0.05$, **$p<0.01$, ***$p<0.001$, all points apply to Figs. 2 and 3).

the SOA of 0 ms, the O condition was significantly faster than the unrelated condition, $p<0.001$, and the P condition was significantly faster than the unrelated condition, $p = 0.001$; at the SOA of 100 ms, the O condition was significantly faster than the unrelated condition, $p = 0.008$, and the P condition was significantly faster than the unrelated condition, $p = 0.004$; there were no significant effects at other SOAs (Fig. 1, right). Results revealed that orthography and phonology were activated simultaneously (SOA = −200 ms) for proficient bilinguals, while the activation of orthography (SOA = −200 ms) was earlier than that of phonology (SOA = 0 ms) for non-proficient bilinguals. The conclusion on the RTs was consistent with that of the separate analysis.

Analysis of the WRD showed that the three-way interaction was insignificant, $F(8, 645) = 1.11$, $p = 0.356$. Planned comparisons revealed no linguistic effects on typing motor execution for proficient bilinguals ($ps>0.518$) (Fig. 2, left), supporting the serial model, while orthographic priming effects at the SOA of −200 ms ($p = 0.008$) and 0 ms ($p = 0.006$), as well as a phonological inhibition at the SOA of 100 ms ($p = 0.048$) (Fig. 2, right), in line with the cascade model. The conclusion on the WRD was inconsistent with that of the separate analysis for proficient bilinguals. However, it was in line with our hypothesis.

Analysis of the IKIs showed that the three-way interaction was insignificant, $F(8, 645) = 1.27$, $p = 0.272$. Planned comparisons revealed no linguistic effects on writing motor execution for proficient bilinguals ($ps>0.374$) (Fig. 3, left), supporting the serial model, while there was a phonological inhibition at the SOA of 100 ms ($p = 0.046$) for non-proficient bilinguals (Fig. 3, right), in line with the cascade model. The conclusion on the IKIs was consistent with the separate analysis.

In sum, comparing the results of the combined analysis with the results of the original analysis, we found that most of the conclusions of the two statistical methods were consistent, except for proficient bilinguals did not show a phonological facilitation effect at the SOA of 0 ms ($p = 0.518$), indicating that proficient bilinguals' typing execution is not affected by the linguistic processing, supporting the serial model, which was consistent with our hypothesis. The reason why we originally designed two separate experiments, rather than putting the two types of participants in one experiment, was that the original research question under investigation was the phonological and orthographic processing during L2 typing production. Based on the current results of the separate experiments, even if the two types of participants were not put together, the trends of phonological and orthographic processing could be reflected to a certain extent. The combined analysis puts the data of the two types of participants together, which can consider the factors and

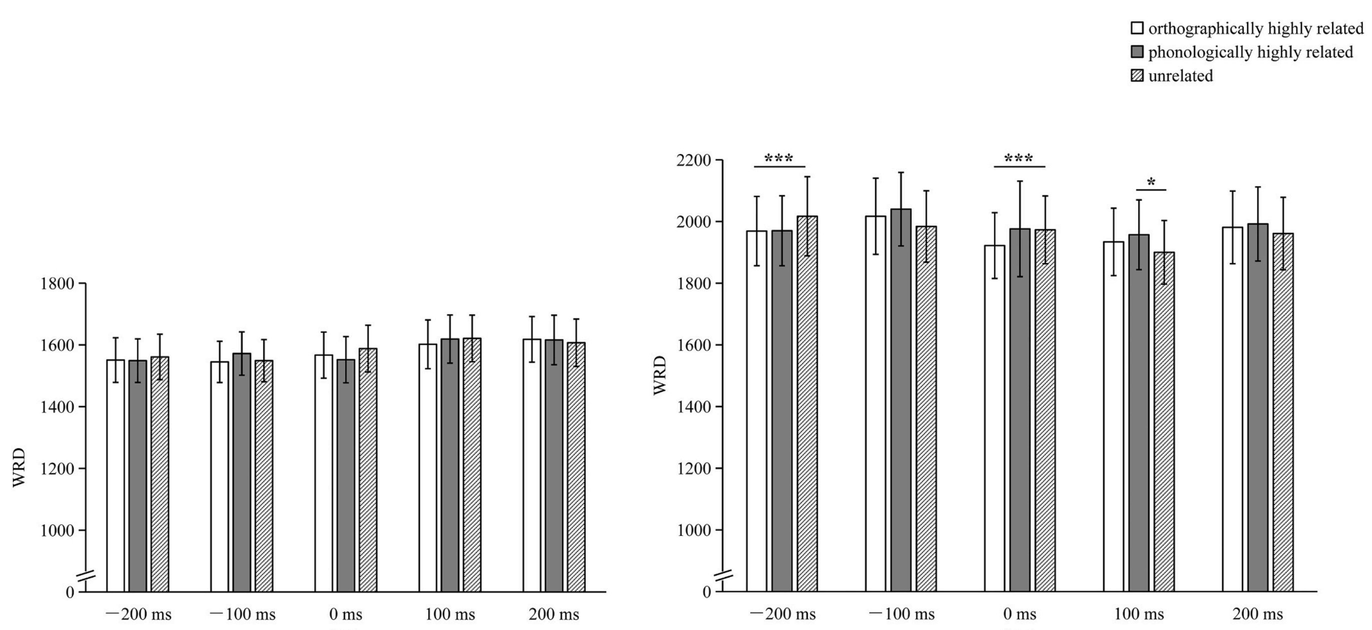

Fig. 2. WRD at each SOA of proficient bilinguals (left) and non-proficient bilinguals (right).

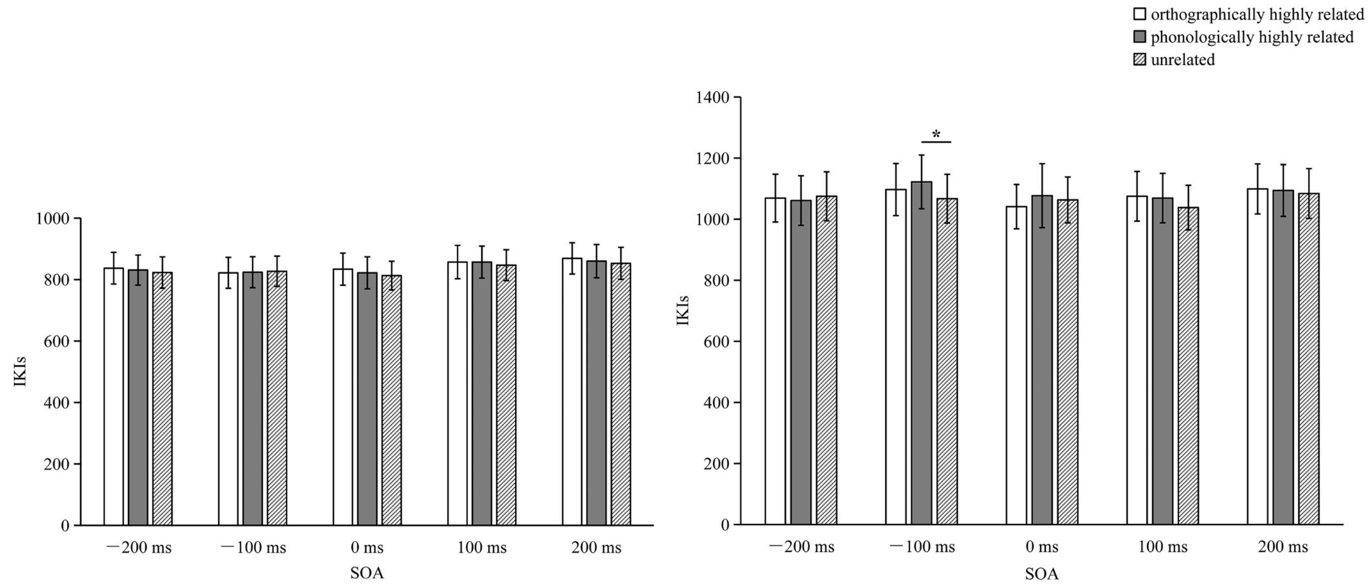

Fig. 3. IKIs at each SOA of proficient bilinguals (left) and non-proficient bilinguals (right).

their internal relationships more comprehensively in revealing this issue.

The overall results in both Experiment 1 and Experiment 2 showed that the effects of phonology and orthography on motor execution might be modulated by L2 proficiency. We suppose that the findings may be attributed to the differences in the quality and accessibility of phonological and orthographic representations during motor execution for bilinguals with different L2 proficiency (Claessen et al., 2009; Perfetti & Hart, 2002). Therefore, Experiment 3 was conducted with the sound discrimination task and the spelling discrimination task to test our interpretation.

4. Experiment 3

4.1. Participants

Participants were 30 proficient and 30 non-proficient bilinguals (the selection criteria are the same as Experiments 1 and 2), who had not participated in the previous experiments. They were all right-handed and had normal hearing without speech, language, or neurological disorders. All the participants received compensation after they completed the whole experiment.

4.2. Materials and design

Materials included 20 target words (the formal pictures' names in Experiments 1 and 2), 20 orthographically highly related, 20 phonologically highly related, and 20 unrelated words to the targets (the three types of distractor words in Experiments 1 and 2).

The experimental design of the sound discrimination task and the spelling discrimination task were both a single-factor design with the Bilingual Type (proficient bilinguals, non-proficient bilinguals) as the between-subjects variable. Both RTs and ACC were recorded.

4.3. Procedure

The whole experiment was conducted via the *E*-Prime software. The participants were tested individually and completed the two tasks without feedback. The sound discrimination task included 20 trials. In each trial, the participants saw a sequence consisting of a fixation cross (500 ms), a blank screen (500 ms), and then a target word was presented acoustically followed by the three types of related words visually, accompanied respectively by the number of 1, 2, 3. The participants were required to select the most phonologically related word to the target and press its corresponding button on the keyboard. The inter-trial interval was 1000 ms.

The spelling discrimination task also consisted of 20 trials. In one trial, participants saw a sequence consisting of a fixation cross (500 ms), a blank screen (500 ms), then a target word was presented visually (1000 ms) followed by the three types of related words, accompanied respectively by the number of 1, 2, 3. The participants were required to select the most orthographically related word to the target and press its corresponding button on the keyboard. The inter-trial interval was 1000 ms. RTs (from the onset of the distractor words to the response) and ACC were recorded for the two tasks.

4.4. Results

We analyzed the participants' performance in the two tasks, respectively, with the independent sample *t*-test on RTs and ACC.

4.4.1. The sound discrimination task

RTs for correct naming trials over 2.5 *SD*s above or below the mean of each condition (3.1 %) were excluded from the analysis. The independent sample *t*-test on RTs showed that the responses of proficient bilinguals were faster than those of non-proficient bilinguals (diff = 864 ms: 3300 ms vs. 4164 ms, $t(58) = 2.11$, $p = 0.035$).

A parallel analysis was conducted on the ACC. Results showed that proficient bilinguals' accuracy rates were higher than those of non-proficient bilinguals (diff = 0.18: 0.68 vs. 0.50, $t(58) = 5.25$, $p<0.001$).

The results of the sound discrimination task indicated consistently that proficient bilinguals' quality and accessibility in phonological representation were better than non-proficient bilinguals.

4.4.2. The spelling discrimination task

RTs for correct naming trials over 2.5*SD*s above or below the mean of each condition (2.1 %) were excluded from the analysis. The independent sample *t*-test on RTs showed no significant difference between proficient and non-proficient bilinguals (diff = 8 ms: 1176 ms vs. 1168 ms, $t(58) = 0.11$, $p = 0.915$).

A parallel analysis was conducted on ACC. Results showed no significant difference between proficient and non-proficient bilinguals (diff = 0.01: 0.97 vs. 0.96, $t(58) = 0.19$, $p = 0.851$).

The results of the spelling discrimination task indicated consistently that there were no differences between proficient and non-proficient bilinguals in the quality and accessibility of orthographic representation.

5. General discussion

In the current study, we set out to investigate whether phonology influences the output of orthography and how phonology and orthography processes affect motor execution during L2 typing production. Proficient and non-proficient Chinese-English bilinguals performed a PWI task in which they were required to typewrite the English names of pictures while attempting to ignore written distractor words. The results from Experiments 1 and 2 showed that the effects of phonology and orthography on typing execution might be potentially modulated by L2 proficiency. Experiment 3 with the sound discrimination task and the spelling discrimination task revealed that the above findings might be due to the characteristics in the quality and accessibility of phonological and orthographic representations for bilinguals with different proficiency.

5.1. The role of phonology in orthographic access of L2 typing production

There have been controversial discussions on whether phonology influences orthographic access during handwritten production with English as the native language (Zhang & Damian, 2010), as well as Chinese as the native language (Qu et al., 2011; Zhang & Wang, 2015). However, no consensus has been reached on their conclusions. By analyzing and summarizing the existing related studies aforementioned in the part of instruction, we are inclined to support Zhang and Wang (2015)'s orthographic autonomy view of orthography is activated earlier than phonology does for Chinese native writers. Given the potential effects of the native language's writing experience on L2 written production, it is essential also to understand whether L2 orthographic access would be constrained by phonology. Our results of Experiments 1 and 2 showed that L2 orthographic activation is not later than phonological activation for both proficient and non-proficient bilinguals, supporting the orthographic autonomy view. Based on the hypothesis of assimilation and accommodation for L2 processing proposed by Perfetti et al. (2007), the obtained pattern of our results demonstrated that Chinese-English bilinguals tended to adopt the mechanism of L1 orthographic access to assimilate that of L2 orthographic access. This is mainly attributed to the influence of L1 writing experience on L2 written production. Regarding the unique characteristics of the Chinese writing system, such as its logographic nature, various strokes and radicals, visual and spatial complexity, and uncertain phonetic relations, learning and mastering the Chinese writing system requires more visual attention and direct form-meaning memory. It could be the case that Chinese native speakers were more dependent on direct visual memory of orthographic-semantic association rather than phonological processing strategies in Chinese character learning because of the opaque feature (Gao & Zhang, 2005; Tao et al., 2007). In addition, in terms of the relative orthographic depth of bilinguals' two languages, our result is consistent with meta-analytic findings on bilingual neuroimaging studies, which indicate that bilinguals adopt the native assimilation strategy to process L2 in the case of Chinese-English bilinguals that L2 orthographic transparency is higher than that of L1, as less cognitive effort would be required during L1 assimilation than L2 accommodation (Liu & Cao, 2016; Xin et al., 2020).

Bilinguals' role of phonology in orthographic access might be modulated by L2 proficiency. For proficient bilinguals, both orthographic and phonological priming effects occurred simultaneously at the SOA of −200 ms. The orthographic and phonological priming effects at the negative SOA suggest that the advanced presentation of the L2 distractor word, whose orthographic or phonological information is activated early, will transfer the activation rapidly to the orthographic representation or phonological representation corresponding to the picture name due to the highly orthographic or phonological relationship with the subsequently presented picture name, facilitating the naming response to the picture. This result suggests that semantics can activate both orthographic and phonological representations simultaneously. For non-proficient bilinguals, the orthographic priming effect occurred at the SOA of −200 ms, while the phonological priming effect occurred at the SOA of 0 ms, indicating that semantics activate orthography earlier than phonology in the cognitive encoding phase. Based on the previous studies (Claessen et al., 2009; Perfetti & Hart, 2002), we inferred that these differences and similarities between proficient bilinguals and non-proficient bilinguals might be due to the characteristics in the quality and accessibility of phonology and orthography for bilinguals with different L2 proficiency. More importantly, further evidence for our inference is provided by the results of Experiment 3. In Experiment 3, we found that proficient bilinguals' phonological representation quality and accessibility were better than those of non-proficient bilinguals, while there was no difference in the quality and accessibility of orthographic representation between the two groups. For proficient bilinguals, this pattern may be due to their strong phonological awareness with years of English education, which leads to more phonological processing strategies during English written production (Gao & Zhang, 2005). For non-proficient bilinguals, this may be due to their extensively transferring direct visual memory strategies of Chinese character learning to English learning, resulting in stronger orthography-semantic associations than semantic-phonology or phonology-orthography associations in English typing. In other words, non-proficient bilinguals' efficiency in directly accessing orthography through semantics is higher than the phonological mediator path in typing (Gao & Zhang, 2005; Tao et al., 2007).

5.2. The influence of phonological and orthographic processes on motor execution of L2 typing production

Whether linguistic processes affect typing execution has been debated for several years. Some studies suggested that linguistic processes were terminated before typing execution, which was consistent with the serial model. In contrast, others indicated that linguistic processes could spread into the execution, which was in line with the cascade model. To address this controversy, the current study investigated the influence of phonology and orthography on motor execution with the PWI paradigm. The overall results in Experiments 1 and 2 showed that the effects of phonology and orthography on motor execution might be moderated by L2 proficiency. Specifically, for proficient bilinguals, results showed no linguistic information affected WRD or IKIs, revealing that the orthographic and phonological processing is terminated before the typing motor execution. In contrast, for non-proficient bilinguals, results found the influences of orthographic and phonological effects on WRD and IKIs, indicating that linguistic processing is still active in the motor execution phase. Taken together, the patterns of results provide evidence for our hypothesis that proficient bilinguals are in line with the serial model while non-proficient ones are for the cascade model.

Our findings are consistent with Bosga-Stork et al. (2016). According to his proposition, for proficient bilinguals, once their typing motor execution has reached a certain level of development, it seems to become an autonomous system, relatively independent of the cognitive coding system. This may be because proficient bilinguals' phonology and orthography have been fully processed in the cognitive coding phase and no further work is needed during the motor execution phase. Furthermore, for non-proficient bilinguals, the influence of orthographic and phonological effects goes in the opposite direction, with orthography promoting the WRD at SOA of −200 ms and 0 ms, while phonology inhibiting the IKIs at the SOA of −100 ms and ultimately delaying WRD at the SOA of 100 ms. This may be due to our findings from Experiment 3 that non-proficient bilinguals' orthographic representation has higher quality and accessibility than phonological representation, leading to the former's retrieval easier than the latter. In addition, given that the two pronunciations (/ɪə/ vs. /eə/) of compound vowels (e.g. "ea") for some of our materials may have different frequencies in fact, the higher the frequency of one pronunciation, the easier it is to be activated, and the greater its effect as a distractor word. In this context, a certain level of proficiency has to be reached to even know that "near" and "bear" are not pronounced the same. However, it is challenging for non-proficient bilinguals to distinguish the different pronunciations due to their poor quality and accessibility of phonological representation, which leads to the phonological inhibition effects on the WRD and the IKIs during typing motor execution.

5.3. Limitations

Several potential limitations should be noted. First of all, our orthographically highly related distractors (*near-bear*) had some degree of phonological overlap with the target name (in this case, the final phonemes/ə(r)/). Similarly, our phonologically highly related distractors (*chair-bear*) included some degree of orthographic overlap (in this case, the final grapheme 'r'). This was due to the inherent confound between sound and spelling in English. However, as our two experiments demonstrate, the two conditions indeed deviated in characteristic ways, shedding light on their respective effects on different phases of typing production.

Another potential limitation is that we did not investigate the participants' native Chinese typing production simultaneously, which could have provided a more comprehensive comparison to better reflect the characteristics of L2 typing production. Additionally, the potential influence of L2 backgrounds on phonological and orthographic processing during typing production is a promising area for future research. Furthermore, we suggest that future studies should include bilinguals with different L2 backgrounds (e.g., Chinese-English, Chinese-Russian, Chinese-Japanese) to further explore this aspect.

Finally, although our planned analysis in combined ANOVAs demonstrated significance patterns largely consistent with our previous findings, the three-way interactions did not reach significance. This may be due to the multi-level factorial design and relatively limited sample size in the present study. Therefore, the sample size should be enlarged in the future research to further verify the current findings.

6. Conclusion

The present study explored the phonological and orthographic processing during L2 typing production in Chinese-English bilinguals. In the cognitive coding phase, the activation of orthography was no later than that of phonology for both proficient and non-proficient bilinguals, which was in line with the orthographic autonomy hypothesis, however, the role of phonology in proficient bilinguals was stronger than non-proficient ones. In the motor execution phase, for proficient bilinguals, phonological and orthographic processes were terminated before motor execution, supporting the serial model; for non-proficient bilinguals, these linguistic processes could cascade into motor execution, consistent with the cascaded modal.

CRediT authorship contribution statement

Yueyue Liu: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Deyang Zhang:** Investigation, Data curation, Writing – review & editing. **Yongli Fu:** Investigation. **Yanlou Liu:** Software, Data curation. **Wenguang He:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare no competing interest.

Appendix A

Materials used in Experiments 1 and 2.

Picture Name	Distractor Type		
	Orthographically highly related(O)	Phonologically highly related(P)	Unrelated(U)
bear /beə(r)/	near /nɪə(r)/	chair /tʃeə(r)/	cloud
foot /fʊt/	boot /buːt/	put /pʊt/	sky
shoe /ʃuː/	hoe /həʊ/	true /truː/	bird
key /kiː/	hey /heɪ/	tea /biː/	radio
fork /fɔːk/	work /wɜːk/	talk /tɔːk/	glass
comb /kəʊm/	tomb /tuːm/	foam /fəʊm/	salt
nose /nəʊz/	lose /luːz/	rows /rəʊz/	train
tower /ˈtaʊə/	lower /ˈləʊə(r)/	our /ˈaʊə(r)/	milk
bone /bəʊn/	done /dʌn/	known /nəʊn/	map
bread /bred/	read /riːd/	said /sed/	lion
arm /ɑːm/	warm /wɔːm/	palm /pɑːm/	oil
ear /ɪə(r)/	wear /weə(r)/	deer /dɪə(r)/	bus
leaf /liːf/	deaf /def/	thief /θiːf/	skirt
wood /wʊd/	food /fuːd/	could /cʊd/	rice
cow /kaʊ/	sow /səʊ/	bough /baʊ/	desk
vase /vɑːz/	base /beɪs/	cars /kɑːz/	clock
pear /peə(r)/	hear /hɪə(r)/	air /eə(r)/	snow
sword /sɔːd/	word /wɜːd/	broad /brɔːd/	lake
cough /kɒf/	rough /rʌf/	off /ɒf/	bike
light /laɪt/	eight /eɪt/	bite /baɪt/	fox

Data availability

The experimental data is available at https://osf.io/2esnw/?view_only=0bd5387d643c4313afd01e36fb2d7d5f.

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