Bilingualism: Language and Cognition

cambridge.org/bil

Research Article

Cite this article: Fu, Y., Álvarez, C.J., Bermúdez-Margaretto, B., Afonso, O., Wang, H., & Domínguez, A. (2024). The interaction of central and peripheral processing in L2 handwritten production: Evidence from cross-linguistic variations. *Bilingualism: Language and Cognition*, 1–14. https://doi.org/10.1017/S1366728924000087

Received: 10 June 2023
Revised: 22 January 2024
Accepted: 27 January 2024

Keywords:
Bilingual writing mechanism; Cross-linguistic orthographic variation; Central and peripheral processing; Word frequency; Orthographic consistency

Author for correspondence:
Huili Wang;
Email: wanghl@hzcu.edu.cn

The interaction of central and peripheral processing in L2 handwritten production: Evidence from cross-linguistic variations

Yang Fu[1,2,3], Carlos J. Álvarez[3], Beatriz Bermúdez-Margaretto[4,5], Olivia Afonso[6], Huili Wang[2] and Alberto Domínguez[3]

[1]School of International Studies, Zhejiang University, Hangzhou, China; [2]School of Foreign Languages, Hangzhou City University, Hangzhou, China; [3]Instituto Universitario de Neurociencias (IUNE), Universidad de La Laguna, Tenerife, Spain; [4]Departamento de Psicología Básica, Psicobiología y Metodología de las Ciencias del Comportamiento, Facultad de Psicología, Universidad de Salamanca, Salamanca, Spain; [5]Instituto de Integración en la Comunidad - INICO, Universidad de Salamanca, Salamanca, Spain; and [6]Centre for Psychological Research, Oxford Brookes University, Oxford, UK

Abstract

The current study explores the interplay between central and peripheral processes in second language (L2) handwriting among bilinguals with diverse orthographic backgrounds. Our investigation delves into the cross-linguistic transfer effect in Spanish–English and Chinese–English bilinguals, emphasizing lexical frequency and phoneme-grapheme (P-O) consistency in spelling-to-dictation and immediate copying tasks. Results reveal that the interaction between central and peripheral processes in L2 handwritten production is shaped by the bilinguals' native language (L1) orthographic characteristics. Spanish–English bilinguals exhibited sensitivity to P-O consistency and the spread of this effect from central to peripheral processes throughout both tasks. Conversely, Chinese–English bilinguals showed heightened sensitivity to lexical frequency during orthographic planning and motor execution, particularly in the immediate copying task. In a broader context, these findings suggest that the parallel and cascading coordination of the L2 writing system is modulated by cross-linguistic variations. The implications of our findings hold relevance for handwriting production and bilingualism research.

Introduction

Cognitive operations engaged in handwriting involve essential processes of retrieving linguistic information from the mental lexicon, activating orthographic codes in working memory, and transcribing parameters into motor programming. As posited by the psychomotor model of writing (Kandel et al., 2011; Van Galen, 1991), these conceptual, linguistic, and motor levels of processing can be characterized as either high-level CENTRAL mechanisms by which orthographic forms are assembled and generated lexically and/or sublexically; or low-level PERIPHERAL processes dedicated to the allographic selection, stroke order planning and execution of the motor trace (Delattre et al., 2006; Ellis, 1979; Planton et al., 2013; Purcell et al., 2011; Rumelhart & Norman, 1982; Weingarten, 2005).

In the same vein, prior writing research has become increasingly grounded in the relationship between central and peripheral processes, with two main assumptions being posited. From a feedforward perspective, central and peripheral processes function in an encapsulated manner (Baxter & Warrington, 1986; Meyer et al., 2003; Planton et al., 2013; Purcell et al., 2011). The writing processing steps are sequentially and discretely coordinated; thus, processing at the spelling level has to be completed before the onset of the motor execution (Damian, 2003; Damian & Stadthagen-Gonzalez, 2009). A contrasting assumption against this hypothesis is that for handwriting in the proficient writer, strictly serial processing steps without overlap of different cognitive processes do not seem conceivable since skilled writing is rather automatized, and hence orthographic representations can be processed in tandem with movement execution (Olive, 2014). Functional models therefore assume that levels of processing operate in a cascaded fashion (Van Galen, 1991). Contrary to the discrete view, higher-order linguistic representations in the cascaded architecture continuously spread from central to peripheral levels, thus modulating lower levels of graphomotor production. This allows information to flow downwards to the next level before the preceding level of processing has finished, with feedback from graphomotor to spelling processes. Attempts to further solidify this claim

This article has earned badges for transparent research practices: Open Data and Open Materials. For details see the Data Availability Statement.

come from studies that used different languages to examine the interaction between spelling processes and motor execution, including Spanish (Afonso et al., 2015a; e.g., Alvarez et al., 2009; Suárez-Coalla et al., 2018), French (e.g., Delattre et al., 2006; Kandel & Perret, 2015; Roux et al., 2013), English (Kandel et al., 2013), Italian (Kandel et al., 2019) and Chinese (Lau, 2021; R. Wang et al., 2020; Zhang & Feng, 2017). To date, previous lines of research exclusively focused on cascading levels of processing in the native language (L1). Moving along this direction, the current research is concerned with investigating cross-writing system variations in the establishment of central-peripheral interactions under the scenario of the second language (L2) handwritten production.

Concretely, we evaluated the impact of lexical and sublexical information on the spelling and graphomotor processes during L2 English word writing across Chinese–English versus Spanish–English bilinguals. We then asked whether the interaction of central and peripheral processes occurs in L2 handwritten production and if it does, to what extent central lexical and/or sublexical processing cascade over motor execution as a function of bilingual L1 (i.e., morpho-syllabic vs. alphabetic) backgrounds. Before presenting the details of the experiment reported below, we 1) briefly characterize the dual-route model in monolingual literature and its variations, 2) recapitulate the evidence for cross-writing systems transfer in L2 word reading procedures so far, and 3) propose hypotheses of L1-L2 transfer effects on L2 written production.

Monolingual writing: the theoretical account of the dual-route processes

In the monolingual spelling literature, neuropsychological models of spelling to dictation (Folk et al., 2002; Houghton & Zorzi, 2003; Tainturier & Rapp, 2001) and/or immediate copying (Bonin et al., 2001; Fernando, 2000) generally include two parallel routes to drive the spelling of words, which would be determined mainly by the linguistic properties of the target word. The lexical route retrieves known orthographic codes from long-term memory, and the relative strength of activating this route would increase with the rate of occurrence of orthographic forms (i.e., lexical frequency). In contrast, the sublexical route computes the spelling of unfamiliar or novel words by relying on the phonology-to-orthography (P-O) consistency system. The degree of P-O consistency is a function of the proportion of words with a similar orthographic representation of a given phonological unit and all other words in which the same unit is represented orthographically otherwise. This measure therefore commonly taps into central processes at a sublexical level. The output from lexical and/or sublexical sources is then stored in the graphemic buffer (i.e., orthographic working memory system) that acts as an interface between central and peripheral processes. Although lexical and sublexical procedures are demonstrated to interact at the graphemic stage and share a common graphemic buffer (Bosse et al., 2003; Houghton & Zorzi, 2003; Roux & Bonin, 2012; Tainturier et al., 2013), it is still an ongoing issue of which levels of linguistic information flow between central and peripheral processes, and the extent to which the working memory capacity is available for cascading coordination of the written production system. In this sense, accumulative empirical findings (see below) support the idea that the activation of lexical and sublexical representations cascades from spelling to graphomotor processes, but their strength can be quantified by various factors.

First, the functional involvement of two processing routes depends on the type of task used for spelling. Bonin et al. (2015) demonstrated a reliable effect of P-O consistency at the central level (evidenced by writing latency) in the spelling-to-dictation but not in the immediate copying task. The peripheral manifestation of the consistency effect (marked by letter/inter-letter interval duration), however, has been documented in both tasks, indicating the application of sublexical information involved in the temporal execution of orthographic forms (e.g., Afonso et al., 2015a, 2015b; Lambert et al., 2011). In parallel, the influence of lexical frequency on the time taken to initiate a graphomotor response has been repeatedly detected across tasks (Bonin et al., 2015; Roux et al., 2013), while its influence on motor execution decreases among writers as they advance along the literacy/writing acquisition trajectory. This pattern has been confirmed by developmental studies (Afonso et al., 2018; Suárez-Coalla et al., 2018) documenting a more apparent effect of lexical frequency in younger than older children (see also the different pattern in Kandel & Perret, 2015; Lau, 2019), and by research on dyslexia where the magnitude of the frequency effect was larger for dyslexic than for typical readers (Afonso et al., 2015a, 2020). Lastly, the locus of lexical and sublexical effects varies depending on the lexical status of the target word. Roux et al. (2013) reported a salient lexical property (i.e., lexicality effect) in letter duration, but it was restricted to the first letters of the item. Sublexical P-O consistency, on the other hand, affected the writing execution for the initial letter when the irregular segment was placed in the beginning (e.g., MONSIEUR), while letter durations were lengthened when the irregularity was at the final position (e.g., INSTINCT). The authors thus concluded that central lexical and sublexical processes influence the kinematics of movement production but do not cascade to the same extent during handwritten production.

The aforementioned theoretical accounts and studies collectively provide essential proof of concept in favor of the interactive and cascaded functional architecture and its modulation by the input modality, age, or the target word's characteristics. Importantly, however, questions remain in regard to whether the involvement of lexical and sublexical processes varies as a function of orthographic systems and if it is true, how variation in L1 literacy backgrounds gives rise to variabilities in L2 handwritten production.

Bilingual reading: the underlying mechanism of cross-language transferring

In the context of reading, contemporary models of bilingual word recognition (BIA, BIA+, Dijkstra et al., 1998; Dijkstra & Van Heuven, 2002) or production (RHM, Costa et al., 1999; Kroll et al., 2010; Kroll & Stewart, 1994; Kroll & Tokowicz, 2005) have settled on a general assumption that lexical representations in bilingual language systems are accessed in a non-language-selective manner. Nonetheless, such co-activation does not necessarily guarantee that all linguistic components of L1 and L2 reading networks are always triggered simultaneously, which indeed, would be modulated by the type of reading strategy and the degree of proficiency in each language. Relatedly, the orthographic depth hypothesis (Frost et al., 1987) predicted that shallow orthographies (e.g., Spanish/German, de León Rodríguez et al., 2016; Perry & Ziegler, 2002) tend to involve more sublexical decoding-like processing. In contrast, deeper orthographies (e.g., French/Dutch/Chinese, see Lallier & Carreiras, 2018 for review) are likely to activate a lexical reading-like pattern primarily, retrieving phonological information through access to the mental lexicon (see also the psycholinguistic grain size theory by Ziegler et al., 2001; Ziegler & Goswami, 2005). Therefore, the varying depth of grapheme-to-phoneme correspondences across different orthographies may determine how words are processed based on sublexical grapheme-phoneme relation and contribute to the organization of orthographic representations at the lexical level as well.

Accordingly, the sensitivity to L1 orthographic-specific features would be transferred non-optimally to guide the employment of dual-route procedures in L2 scripts. The idea is partly supported by prior research with between-group designs of different L1 backgrounds. For instance, Hamada and Koda (2008) measured the L2 English reading performance between Korean–English and Chinese–English bilinguals. They reported that compared to Korean–English bilinguals, whose L1 orthographic background is congruent with English as an L2 (i.e., both are alphabetic writing systems), Chinese–English bilinguals showed less sensitivity to the phonological properties of L2 English scripts and stronger sensitivity to lexical frequency. In their later work, Hamada and Koda (2011) further explored similarities and differences in L2 visual word learning by comparing Korean and Chinese bilingual groups. The Korean group showed more sensitivity to phonological features of novel L2 words than the Chinese groups, as evidenced by a significant effect of the P-O regularity. These results illustrated that L2 readers with divergent L1 orthographic depths adopt systematically different processes towards the use of lexical versus sublexical reading strategies, in support of cross-linguistic transfer effects on the bilingual reading procedures (Akamatsu, 1999, 2002; Ben-Yehudah et al., 2019; Hamada & Koda, 2010; M. Wang & Koda, 2005, among many others)

In parallel with those studies concerned with cross-writing systems transfer in reading, it is reasonable to expect that variation in the L1 alphabetic versus morpho-syllabic background should impact L2 handwritten production. However, to our knowledge, there is currently no direct evidence or specific data supporting this assumption. Still, no hypotheses or predictions are made on whether L1-specific orthographic knowledge modulates the central-peripheral interaction of L2 scripts, particularly those with varying degrees of orthographic depth, and the ensuing effect on the internal organization of the bilingual spelling system. As such, the proposed relationships among bilinguals' L1 orthographic backgrounds, L2 input properties, and L2 handwritten production are argued for in the present study.

Bilingual writing: the putative influence of L1 orthographic-specific variations

We propose that the coordination of online L2 handwriting processes will be influenced by the characteristics of the L1 orthography. Although the distinction in orthographic depth does not hold up to direct scrutiny in peripheral writing mechanisms, potential issues regarding the mediating role of phonological information are implied in prior research on the Spanish and Chinese populations, respectively.

The writing models of alphabetic languages converge in representing two key cognitive processes in handwritten production (e.g., Bonin et al., 2001; Fernando, 2000). The semantic system is symmetrically connected to orthographic and phonological output lexicons, with entries in the graphemic buffer being selected either directly through semantic code activation (i.e., the orthographic autonomy route, Miceli & Miceli, 1997; Rapp et al., 1997) or indirectly via the phoneme-to-grapheme conversion (i.e., the phonological mediation route, Basso et al., 1978; Geschwind, 1974). Specifically, skilled Spanish writers are documented to exhibit more weights of the sublexical P-O consistency than lexical word frequency (Afonso et al., 2015a, 2020; Kandel & Valdois, 2006; Suárez-Coalla et al., 2016, 2018, 2020) – even in the immediate copying task involving known words (e.g., Afonso et al., 2015a) – implying the application of phonological mediation in the selection, activation, and execution of constitutive letters in a transparent orthography (see Kandel et al., 2019, for similar results in Italian). Furthermore, evidence for explaining the absence of lexical frequency effect in the peripheral processing of Spanish words was determined by Afonso et al. (2018). The authors contended that due to the less conflict and interference between lexical and sublexical processing in Spanish, skilled writers could effectively assemble orthographic units at the sublexical level, thereby producing accurate spellings for the majority of words.

In contrast, Lau (2019) found opposite results compared to Afonso et al. (2018): the effect of radical frequency elicited by Chinese characters was robust in Chinese children with developed writing skills. The data pointed to the evidence that skilled Chinese writers are able to take advantage of the combined graphomotor patterns of both small and large orthographic units. Indeed, Chinese is a morpho-syllabic language in which characters consist of interwoven strokes that are packed into a square-shaped form, and each graphic symbol corresponds with a morpheme. As Seidenberg (1985) noted in Chinese, "*more direct encoding of phonological information only provides an advantage for low-frequency, more slowly recognized lexical items*" (p20). Thus, notwithstanding conflicting findings concerning the phonological effects on orthographic access (e.g., Qu et al., 2011; Zhang & Wang, 2015), Chinese orthographic codes in general can be directly retrieved from semantic input without requiring phonological mediation. More recently, studies using writing-to-dictation paradigms have revealed that the P-O consistency effect on Chinese handwritten production is dominant in early writing preparation but has not emerged at the later stage of handwriting execution (Lau, 2021; R. Wang et al., 2020). This evidence implies that Chinese writers may solve phonological conflicts before starting to write. Further, the effects of lexical frequency extend from the central processes of orthographic planning to the peripheral processes of motor execution. Therefore, a variety of findings make clear that handwritten production in Spanish orthography demonstrates significant P-O consistency effects on linguistic access and movement production, whereas the lexical-semantic procedure might be exceptionally critical in the identification of Chinese orthographic units in writing. We then expect these variabilities in the orthographic features of the L1 writing systems to modulate bilingual differences in the involvement of lexical and sublexical variables in L2 word written production.

The present study

To re-iterate, the current work focuses on the interaction of central and peripheral processes during L2 handwritten production. Importantly, we sought to examine whether the same cross-linguistic transferring effect can be found in writing when considering L1-L2 language pairs with relatively similar or entirely dissimilar orthographies. With this in mind, two orthographically distinct groups of Spanish–English and Chinese–English

https://doi.org/10.1017/S1366728924000087 Published online by Cambridge University Press

bilinguals were instructed to write English words as their shared L2. English, considered an "outlier orthography" (Share, 2008; Section 1.1), is a deeper alphabetic language with a high degree of inconsistency in its spelling-to-sound mappings. Hence, in English, the spelling system requires not only a route involving direct grapheme-phoneme mappings but a lexical-based mechanism to produce the word spelling. This feature of English orthography allows us to identify differences in the extent to which bilinguals with shallow and deep L1 orthographic backgrounds are biased toward sublexical versus lexical writing procedures.

In the experiments reported here, two groups of bilinguals participated in spelling-to-dictation and immediate copying tasks in which lexical frequency (as a genuine index of the mobilization of the lexical procedures) and P-O consistency (as a signature of the involvement of the sublexical procedures) were manipulated. We used Bayesian multilevel regression predicting a range of offline (i.e., accuracy) and online measures (see below) from population-level effects of lexical frequency and P-O consistency. Following the shared method (e.g., Bonin et al., 2015; Kandel et al., 2011), writing latency (the time between the onset of the stimulus and the occurrence of the first contact of the pen with the paper) is applied as a central measure to capture the planning of handwritten responses. In terms of peripheral metrics, multiple options in the nature of selected stimuli and temporal measures were available, yet the current experiment can engender only one set of choices that we believe would prioritize our main research questions. As manifested by Roux et al. (2013) and many others, lexical and sublexical variables affect peripheral processes specifically during the execution of the initial letters. We thus considered the writing duration of the first letters (i.e., critical segment) as an indicator of the peripheral processes. Additionally, we took the inter-letter interval located before the critical grapheme (which varied degrees of phonological consistency) into account, since it may reflect the accessibility of the intervening phoneme during the writing movement (Afonso et al., 2015a).

The hypotheses of the current study stem from the theoretical accounts and collective implications provided by the research reviewed above. We predict that, in general, variations in the relative use of the lexical and sublexical routes associated with the characteristics of the bilinguals' L1 spelling system would transfer to L2 handwritten production, with stronger effects of lexical frequency exhibited by the Chinese group and a greater sensitivity to P-O consistency shown in the Spanish group. We also expect that these biases would affect both the central levels of activation and real-time motor execution of target orthographic codes and thus be in consonance with the cascaded version of the model (Van Galen, 1991). Further, since more reliable effects of P-O consistency have been reported in spelling-to-dictation than in immediate copying tasks (Bonin et al., 2015), we hypothesize that both Chinese and Spanish groups would be sensitive to the P-O consistency during the retrieval of orthographic codes in spelling-to-dictation task. As the immediate copying task is generally believed to be carried out via lexical access, we do not put forth a hypothesis involving the cascading activation of phonology from central to peripheral processes within this task, particularly for Chinese–English bilinguals.

Methods

Participants

One hundred ninety-six individuals (see Session 2 in the online supplementary materials S1 for the consideration of power estimation) completed a battery of preliminary online assessments where each participant took part in a Language History Questionnaire (LHQ 3.0, Li et al., 2020), the LexTALE test (Lemhöfer & Broersma, 2012), two custom-made tasks (Spoonerism, Brunswick et al., 1999; Phoneme Deletion, M. Wang et al., 2003), and a standardized test (Nonword Repetition, CTOPP; Wagner et al., 1999). The procedure of preliminary assessments is detailed in Session 1 in the online supplementary materials S1. The pool of participants was filtered to ensure participants self-reported as being Spanish/Chinese–English sequential bilinguals with English as a second language and having a high-intermediate level of English proficiency with relatively developed phonological abilities. Therefore, we excluded any participants who responded that they were proficient in a second language other than English, or that score means for individuals did not fall within the expected ranges on all preliminary tests. The final sample comprised 64 Spanish–English bilinguals (21 males, $M_{age} = 21.3$, $Range_{age} = 18\text{-}23$) recruited from Universidad de La Laguna (Spain) and 68 Chinese–English bilinguals (28 males, $M_{age} = 21.8$, $Range_{age} = 18\text{-}25$) from Dalian University of Technology (China). All participants reported normal or corrected-to-normal vision and were non-English-major college students with no evidence of reading, motor, or perceptual disorders. Participants gave informed written consent prior to participation. Ethical approval for the study was provided by the Research Ethics Committee of Universidad de La Laguna (Comité de Ética de la Investigación y Bienestar Animal, Registration number: CEIBA2021-3104).

Figure 1 displays a radar plot summarizing the assessment data across two bilingual groups. A Bayesian two-sample t-test for responses on the LHQ 3.0 and the LexTALE test indicated that the bilingual groups did not differ significantly in their English proficiency or current use of English (Immersion experience). In addition, the two groups were matched in their scores on Spoonerism, Phoneme Deletion, and Nonword Repetition tasks. Please refer to Table S1 in the online supplementary materials S1 for mean by-participant accuracy levels, standard deviation, and t-test statistics for scores of each assessment. Thus, we controlled that the bilingual groups exhibited similar profiles of L2 linguistic proficiency and phonological abilities.

Materials

Thirty-two English words served as the experimental stimuli which were orthogonally varied in their initial P-O consistency and lexical frequency (e.g., consistent phoneme a→/æ/ in manage and malice; inconsistent phoneme a→/ə/ in machine and maroon). Regarding the P-O consistency manipulation, we computed consistency values across orthographic forms from the recent work by Chee et al. (2020), which quantifies spelling-to-sound relationships based on a corpus of 37,677 English monosyllabic and multisyllabic words. The consistency ratio was operationalized as weights of FRIENDS (i.e., words with similar orthographic forms shared the same pronunciation) and ENEMIES (i.e., similarly spelled words with different pronunciations) for the given vowel grapheme (i.e., nucleus) within the first syllable. For instance, m(a→/æ/) in the stimulus *manage* has more FRIENDS than m(a→/ə/) in the MACHINE. Here note that the decision to focus on consistency at the level of oncleus (i.e., the concatenation of the onset and the nucleus) differs from traditional investigations where consistency was generally manipulated in terms of the body-rime correspondences (the

https://doi.org/10.1017/S1366728924000087 Published online by Cambridge University Press

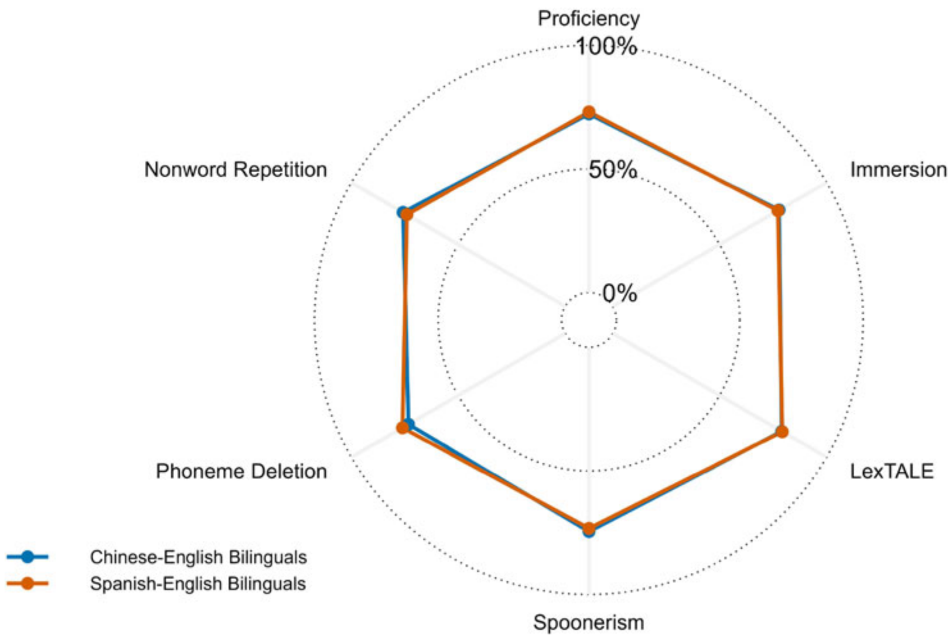

Figure 1. Radar plot of the preliminary assessment data.
Note. Each line represents a bilingual group. Each point represents an average score, scaled to range from 0 to 1, for a given metric of each test. Preliminary tests include: LHQ 3.0 (Proficiency + Immersion), LexTALE, Spoonerism, Phoneme Deletion and Nonword Repetition.

concatenation of the vowel and the coda, see Jared et al., 1990; Jared, 1997; Lacruz & Folk, 2004; Steacy et al., 2019; Treiman, 2018). Our choice of emphasizing small sub-syllabic grain-sizes was based on prior findings that bilinguals rely more on grapheme-phoneme correspondences than on other orthographic features (e.g., Koda, 2007; Mokhtari & Reichard, 2002). The resulting consistency ratio ranges from 0 (very inconsistent) to 1 (highly consistent).

In designing our stimuli, both TYPE and TOKEN consistency were tapped into. To be specific, consistency based on TYPE estimates was calculated by dividing a given word's number of FRIENDS by the total number of FRIENDS and ENEMIES in the fixed position (i.e., initial or final).

$$Type\ consistency = \frac{no.\ of\ friends}{no.\ of\ friends + enemies}$$

TOKEN consistency weights a given word's *friends* and *enemies* by the sum of the frequency of their occurrence. It is computed by dividing the logarithmic frequencies of FRIENDS by the combined logarithmic frequencies of FRIENDS and ENEMIES.

$$Token\ consistency = \frac{\sum \log freq\ (friends)}{\sum \log freq\ (friends) + \sum \log freq\ (enemies)}$$

In parallel, given the nature of the current experimental setting, a bidirectional activation of phonological representations would stem both from external spoken input in dictation-based spelling task and from inner speech during spontaneous copywriting. Thus, a reciprocal interaction between orthography and phonology was expected, with each influencing and being influenced by the other. By definition, we therefore considered two ratios: one in which a pattern of orthographic codes activates a series of phonological units (henceforth referred to as FEEDFORWARD consistency), and the other where the phonological units feed activation back to the orthographic codes (henceforth referred to as FEEDBACK consistency). Thus, items were controlled in a balanced way with regard to TOKEN/TYPE consistency and FEEDFORWARD/FEEDBACK consistency. That is to say, words with high TYPE/FEEDFORWARD consistency were also consistent in terms of TOKEN/FEEDBACK consistency. Similarly, we chose words with low consistency in both dimensions.

For the lexical frequency manipulation, measures were taken from the SUBTLEX$_{uk}$ corpus (Van Heuven et al., 2014) and expressed as *Zief* values (log10 of per-million-word frequency). The threshold frequency is determined by words with a *Zief* value above 4.0 being categorized as high-frequency words and those below 3.0 as low-frequency words. For the purposes of quantifying the impacts of sublexical and lexical routes on writing production in terms of statistical power and sample sizes, we conceived of P-O consistency and lexical frequency as continuous variables in the following model structures (see Tabachnick & Fidell, 2013 for the advantages of using continuous variables to maximize the information obtained from data; see also Cohen, 2013; Maxwell et al., 2008). The correlation between the two independent variables across items was small (rho = -0.10, 95% Crl [-0.44, 0.25]).

Since letters that vary in the number of strokes might obscure the writing duration (e.g., the absolute duration of the letter E with four strokes will be longer than the letter O with two strokes, see Kandel & Spinelli, 2010), stimuli were matched on the identity of the oncleus within the first syllable structure across conditions to allow for a direct comparison between letters at a given position. The majority of items were monomorphemic (96%), and they were controlled ($F(3,28) = 0.104\text{-}1.867$, $ps > .16$) for word length, number of syllables, number of phonemes, bigram frequency (taken from the British lexicon project, Keuleers et al., 2012), and orthographic neighborhood size (i.e., Coltheart's N, Coltheart et al., 1977; OLD20, Yarkoni et al., 2008; taken from the `vwr` package, Keuleers, 2013). Please refer to Table S2 in the online supplementary materials S1 for the full list of stimuli and their linguistic properties.

For each word, a visual stimulus and an auditory stimulus were created for use in the immediate copying and spelling-to-dictation tasks, respectively. The auditory stimuli were recorded by a male, English native speaker with a neutral accent and filtered from

https://doi.org/10.1017/S1366728924000087 Published online by Cambridge University Press

environmental sounds. The mean acoustic duration of all stimuli was controlled within a range of 796 to 803 ms. Also of note is that the stimuli selected were not cognate words across English and Spanish to avoid any confusion. Six extra words were selected as practice items.

Apparatus and procedure

Stimuli presentation and the recording of written responses were programmed by Ductus software (Guinet & Kandel, 2010). A Wacom Intuos Pro graphics tablet (sampling frequency: 200 Hz) connected to the computer and a ProPen 2 pen (±60-level tilt recognition, ink removal) were used to register the executed movements of the participants. It is worth noting that the experimental procedure was carried out in two separate laboratories located in different countries. For the purpose of data quality control, the first author tested participants in Spain and China, ensuring the implementation of the experiment under a consistent (e.g., the same graphics tablet and verbal instructions) or similar (e.g., the use of similar screens, computer configurations, and soundproof rooms) experimental setting.

Participants first completed the spelling-to-dictation task in order to avoid the orthographic representations of the word being exposed before this task. Each trial began with a simultaneous presentation of an auditory signal and a fixation point in the center of the screen for 500 ms. The auditory stimulus was presented after the offset of the fixation point. In the immediate copying task, each trial started with a 500 ms fixation point, followed by a blank screen for 500 ms, and lastly the presentation of a centered stimulus (18-point lowercase in Times New Roman font) that disappeared after 800 ms. We opted for this procedure to ensure that any potential effect observed in writing duration is attributable to production processes and not confounded by reading, comprehension, or recall processes (see Afonso & Álvarez, 2019). In both tasks, stimuli were presented in a pseudo-random order across the participants.

Participants were instructed to keep the pen hovering in close proximity to a response line drawn on a sheet of paper placed over the graphic tablet, anticipating the required response in advance to minimize extraneous arm movement during each response. Then they had to initiate writing the word in uppercase on the line as quickly and accurately as possible. They were asked to tap the bottom right square of the response sheet with the pen tip to begin the next trial, followed by quickly positioning the pen over the response line again without making any contact with the paper. During the experiment, participants were not able to view their writing trajectory on the computer screen to avoid the influence of visual feedback from previously written outputs.

To verify the accuracy of participants' pronunciation of the English stimuli, a reading-aloud task was administered immediately following the immediate copying task. During this task, participants were instructed to read each word aloud. Single trials in which naming errors were made by participants were correspondingly excluded from the copying task dataset (overall, n =31, 1.1%). This rigorous approach ensured that reading processes in handwritten production were controlled, as the correct pronunciation of the word is linked to the assessment of orthographic sensitivity and thus conducive to its accurate transcription.

Statistical modeling

Statistical analyses are divided into two subsections with 1) population-level effects in the omnibus model of spelling-to-dictation and immediate copying tasks, and 2) individual differences in L2 handwritten production. We refer readers to the online supplementary material S2 for an analysis of individual differences. Writing accuracy was coded as 1 (correct) or 0 (incorrect) in each trial. Writing latency refers to the time between the onset of the auditory/visual stimulus and the occurrence of the first contact of the pen with the graphics tablet. The kinematics of motor production was registered from the *txt* file using custom-designed Matlab code. The writing duration of the critical segment was defined as time elapsing between the first contact with the tablet when writing the onset and the moment the pen lifted after writing the nucleus within the first syllable. Inter-letter interval was measured as the time between the last pen lift in the onset and the first pen lowering in the following nucleus. Data and codes used to reproduce the present study are freely available on the Open Science Framework https://osf.io/2wmsq/.

We conducted all analyses using Bayesian multilevel regression fitted in the probabilistic programming language `stan` (Stan Development Team, 2018) via the package `brms` (Bürkner, 2017, 2018) in the R environment (R Core Team, 2022, v4.2.2). The model predicted outcome variables in the spelling-to-dictation and the immediate copying tasks for the population effects of Language Groups (Spanish–English vs. Chinese–English), P-O consistency (individual values), Lexical Frequency (individual values), and the higher order interactions. The `hypr` package (v0.2.3; Rabe et al., 2020) was called to design sequential difference contrasts for categorical variables (2-level predictors Language Groups: 1/2, −1/2). Continuous variables (P-O consistency and Lexical Frequency) were standardized in the model with a mean of 0 and a standard deviation of 1. Thus, the estimated quantity of the intercept term represented the grand average across conditions. This allows us to estimate the regression coefficients associated with each contrast, and the resulting estimates can be interpreted as simple main effects based on the hypothesis matrix. The likelihood of the model fitted to the writing latency, inter-letter interval, and writing duration data was assumed to be distributed as lognormal. The corresponding logistic models were fitted to the accuracy data with Bernoulli likelihood distributed with a logit linking function. All models were specified with group-level factors for participants and items. A maximal random effect structure was included: the random slope for the P-O consistency by Lexical Frequency interaction varied for the participant level, as did the Language Group for the item level.

The above models included regularizing, weakly informative priors for the intercept and variance components (Gelman et al., 2017), with `brms` default uninformative priors for the slope coefficients to estimate plausible posterior values. Markov Chain Monte Carlo sampling was implemented with four chains distributed between four processing cores to draw samples from the posterior probability distribution. To assess our *a priori* hypotheses, a region of practical equivalence (ROPE) around a point null value of 0 (Kruschke, 2018) was established by using the following formula:

$$ROPE = \frac{\mu_1 - \mu_2}{\sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}}$$

In general, we reported four statistics to describe the posterior distribution for each parameter of interest, including 1) median posterior point estimates, 2) the 95% highest density interval (HDI), 3) the proportion of the HDI contained within the ROPE, and 4) the maximum probability of effect (MPE). For statistical inferences, a posterior distribution for a parameter β in which 95% of the HDI does not contain 0 and falls outside the ROPE as well as a high MPE (i.e., values close to 1) are considered compelling evidence for a given effect.

Results

Word substitutions, missing responses, and disfluencies were coded as errors and were discarded in the spelling-to-dictation (overall, n = 1162; 31.6%) and immediate copying tasks (overall, n = 60; 2%). The inclusion criteria required a minimum individual writing accuracy of 60% in the spelling-to-dictation task, and as such, twelve participants (eight Chinese and four Spanish) who fell below this threshold were excluded from the dataset. Across temporal measures of interest, data points that fell outside a range of ± 2.5 standardized residual errors were removed (model criticism, see Baayen et al., 2008; Baayen & Milin, 2010). The models were afterward re-fitted using the truncated dataset (see Oppenheim, 2018 for a similar procedure; see also Lorenz et al., 2021). This trimming procedure resulted in the exclusion of 66 trials (2.6%) of writing latency, 34 trials (1.4%) of inter-letter interval, and 63 trials (2.5%) of writing duration in the spelling-to-dictation task; and 44 trials (1.2%) of writing latency, 85 trials (2.2%) of inter-letter interval, and 63 trials (1.7%) of writing duration in the immediate copying task. Note that only the interaction terms which are relevant to the research question will be interpreted.

We begin with summarizing the results of the spelling-to-dictation task. Table 1 reports the posterior distribution of the outcome variables.

As illustrated in Figure 2, lexical frequency was associated with an increase in the log odds of responding correctly: words of higher frequency were written more accurately in both language groups. Similarly, writing latencies decreased as lexical frequency increased for both bilingual groups. We also found evidence that the consistency effect was modulated by language groups. Spanish–English bilinguals were faster when responding to words with higher P-O consistency, which was not the case for Chinese–English bilinguals. In terms of peripheral metrics, there was evidence of P-O consistency by frequency interaction on inter-letter intervals, with a stronger lexical frequency effect in words with lower consistency compared to consistent words shown in both groups. Additionally, evidence for the effects of frequency and a three-way interaction among P-O consistency, frequency, and groups on writing durations indicated that lexical frequency was modulated by P-O consistency in the Spanish group, though not for their Chinese counterparts. That is to say, response differences between frequent and infrequent words only appeared in words with lower P-O consistency for Spanish–English bilinguals, while Chinese bilinguals tended to respond faster with increasing lexical frequency.

Regarding the immediate copying task, Table 2 summarizes the posterior distribution of the outcome variables. Writing accuracy in this task was not reported as none of the manipulated variables reached a significant effect.

The diptych plots in Figure 3 illustrate three temporal measures as a function of P-O consistency and lexical frequency that remain constant at standardized values of −1, 0, and +1. We found evidence of frequency effect and a two-way interaction between consistency and groups on writing latencies. The main effect of frequency resembled that in the spelling-to-dictation task, with faster overall writing latencies to words with higher than lower frequency in both bilingual groups. In contrast to performance in the spelling task, higher P-O consistency associated with faster response was evident in the Chinese group, but no such effect was found among Spanish–English bilinguals. However, turning to motor execution, the consistency effect was only observed in the Spanish group, with much faster performance when responding to consistent than inconsistent words, as illustrated by a strong effect of a two-way interaction between P-O consistency and groups on both inter-letter intervals and writing durations. In addition, writing duration decreased as a function of lexical frequency, which was only observed in the Chinese group, as indicated by evidence of a two-way interaction of lexical frequency by groups.

Discussion

The current work revisits the proposed parallel and cascading architecture of handwritten production (Kandel et al., 2011; Van Galen, 1991). Writing latency, an indicator of central processing, was complemented by writing kinematics (i.e., inter-letter interval and writing duration) to elucidate the coordination of the online writing process under a second-language scenario. The functional involvement of sublexical (here, P-O consistency) and lexical (lexical frequency) activation was tapped into the real-time production of word spellings from auditory and visual input. Our results, from a cross-linguistic transferring perspective, provide compelling evidence for the theoretical claim that the flow of higher-ordered linguistic information cascades between central and peripheral levels of processing. Nevertheless, shaping the cognitive and motor program involved in bilingual written production is likely to interact with L1-specific orthographic features across varying task demands. In what follows, we discuss the influence of cross-linguistic variation on the selection and implementation of the handwriting trace in the framework of dual-route models.

Upon comparing the accuracy and/or writing latency data in both tasks, a similar pattern of lexical frequency effect was identified at the group-level performance. L2 words were written more accurately and with shorter latencies as their frequency increased, in line with L1 data (Kandel & Perret, 2015; Roux et al., 2013; R. Wang et al., 2020) that the accessibility of high-frequency words in an individual's mental lexicon leads to greater efficiency in word processing and reproduction. While the employment of the lexical route is comparable in bilingual groups with distinct L1 backgrounds, the sublexical P-O consistency effect exhibits a variation in latencies between the two groups. In the spelling-to-dictation task, full knowledge of phonological consistency was solely evident in writing latencies among Spanish–English bilinguals, inferring that more straightforward mapping between phoneme and grapheme in Spanish orthography fosters the activation of the sublexical route in L2 writing processes. Conversely, the lack of the P-O consistency effect in the Chinese group pointed to the possibility that sublexical processing may be too weak to contribute significantly to orthographic access. The failure in detecting this effect could be attributed to the inherent opaque nature of the Chinese orthography itself – for example, unstable phonological representation of Chinese characters resulting in its poor connection to corresponding orthographic representation. Given the matching of the two

https://doi.org/10.1017/S1366728924000087 Published online by Cambridge University Press

Table 1. Spelling-to-dictation Task: Summary of the posterior distribution modeling writing latency, accuracy, inter-letter interval and writing duration of critical segments as a function of P-O feedforward consistency and lexical frequency. The table includes posterior medians, the 95% HDI, the percentage of the HDI within the ROPE, and the maximum probability of effect (MPE).

Measures	Parameters	Median	95% HDI	ROPE	MPE
Writing Latency	Intercept	7.79	[7.72, 7.85]	0	1
	Consistency	-0.05	[-0.09, 0]	0.17	0.98
	Frequency	-0.13	[-0.18, -0.08]	0	1
	Groups	0.21	[0.10, 0.32]	0	1
	Consistency : Frequency	0	[-0.05, 0.04]	0.78	0.54
	Consistency : Groups	0.1	[0.04, 0.16]	0	1
	Frequency : Groups	0	[-0.07, 0.07]	0.55	0.55
	Consistency : Frequency : Groups	-0.06	[-0.12, 0]	0.12	0.97
Writing Accuracy	Intercept	1.32	[0.78, 1.88]	0	1
	Consistency	0.05	[-0.34, 0.43]	0.4	0.6
	Frequency	0.73	[0.28, 1.14]	0	1
	Groups	0.09	[-0.27, 0.45]	0.39	0.7
	Consistency : Frequency	0.11	[-0.27, 0.49]	0.36	0.72
	Consistency : Groups	0.26	[-0.11, 0.62]	0.18	0.92
	Frequency : Groups	0.4	[-0.01, 0.78]	0.05	0.97
	Consistency : Frequency : Groups	0.03	[-0.32, 0.38]	0.45	0.57
Inter-letter Interval	Intercept	5.67	[5.59, 5.75]	0	1
	Consistency	-0.14	[-0.21, -0.08]	0	1
	Frequency	-0.17	[-0.24, -0.11]	0	1
	Groups	0.24	[0.12, 0.37]	0	1
	Consistency : Frequency	0.12	[0.05, 0.18]	0	1
	Consistency : Groups	0.06	[-0.01, 0.12]	0.07	0.98
	Frequency : Groups	0.05	[-0.01, 0.12]	0.2	0.94
	Consistency : Frequency : Groups	-0.03	[-0.08, 0.02]	0.48	0.84
Writing Duration	Intercept	7.4	[7.33, 7.47]	0	1
	Consistency	-0.04	[-0.09, 0.02]	0.31	0.91
	Frequency	-0.14	[-0.20, -0.08]	0	1
	Groups	0.17	[0.06, 0.29]	0	1
	Consistency : Frequency	0.05	[0, 0.11]	0.14	0.97
	Consistency : Groups	0.08	[0.01, 0.16]	0.04	0.98
	Frequency : Groups	-0.05	[-0.13, 0.03]	0.24	0.9
	Consistency : Frequency : Groups	-0.09	[-0.17, -0.01]	0.01	0.99

groups in language proficiency and other cognitive factors, these systematic differences in procedures may reflect the principles of computational models proposed for bilingual word recognition, which posit that differences in orthographic depth are associated with the conjoint activation of lexical constituents for word identification of both L1 (e.g., Perry & Ziegler, 2002) and L2 (e.g., Koda, 2008). In a parallel manner, our findings build upon and expand these computational works, demonstrating the impact of cross-linguistic transfer on L2 handwritten production.

It is noteworthy that the pattern of P-O consistency at the central level was reversed across groups in the immediate copying task as opposed to the dictation task, with this effect evident in the writing latencies of the Chinese group but absent in their Spanish counterparts. One explanation for this divergent pattern lies in the relationship between the attunement of the handwriting system to high-level linguistic information and the subsequent manifestation of these variables in writing behavior. Dual-route conceptions of spelling propose that writing production can be jointly determined by both lexical and sublexical processing; however, as previously stated, the influence of either depends on its reliability within a given task. In the context of copywriting, the behavioral manifestation of P-O consistency in writing latencies is indicative of the efficiency with which sublexical units guide spelling modules. Specifically, although phonological information

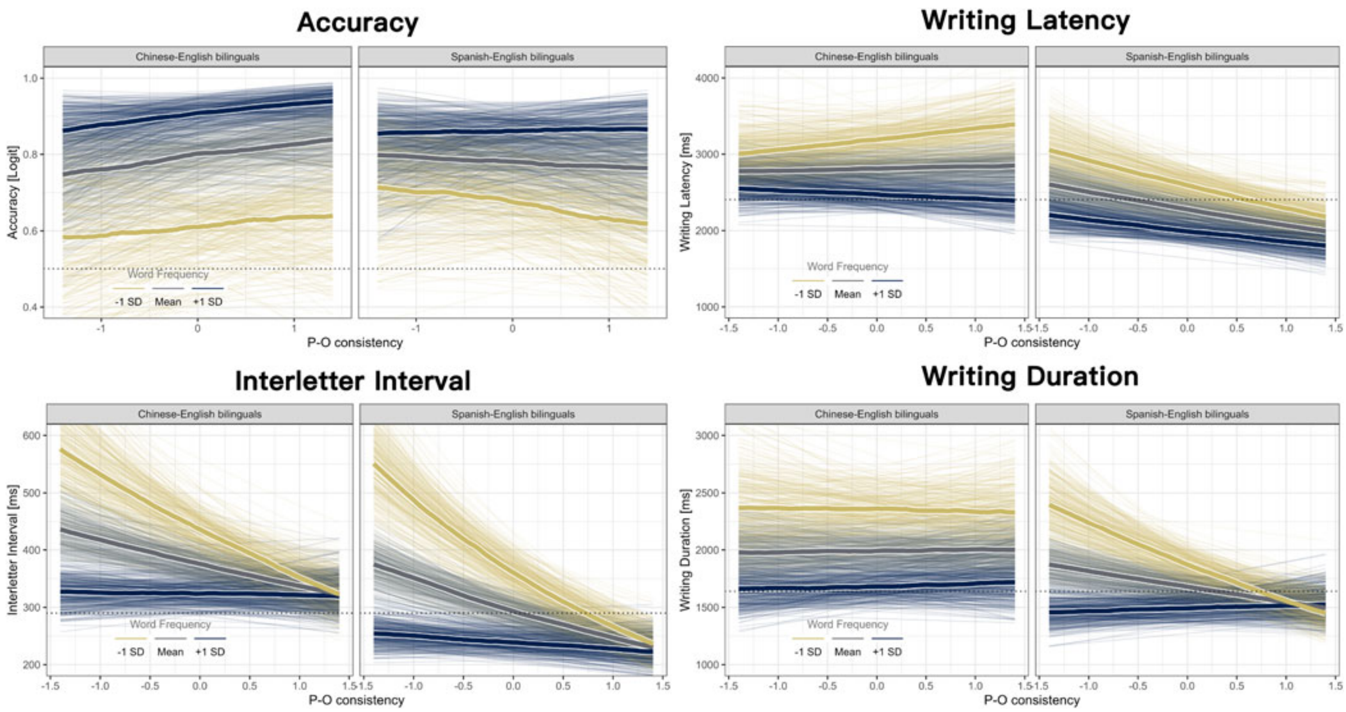

Figure 2. Spelling-to-dictation Task: Probability of a correct response, writing latency, inter-letter interval and writing duration as a function of P-O consistency while holding lexical frequency constant at −1, 0 and +1 standard deviations from the mean.
Note. Thin lines represent 300 draws from the posterior distribution and indicate uncertainty (95% HDI) around the posterior medians (thick lines). The dotted lines indicate the model intercept.

was not consulted at the early stages of orthographic access in the Spanish group, the P-O consistency effect was the only proxy for assembling L2 sublexical units in motor execution. If the orthographic conflict at a sublexical level constituted a supplementary load for inconsistent words during writing preparation, this cognitive load would spread throughout the graphomotor programming. Thus, the sublexical route appears to sustain a considerable degree of activity in the copying task, not necessarily before the initiation of movement (see Roux et al., 2013 for similar results). In the case of Chinese bilinguals, they generally activate the orthographic representation of an inconsistent word stored in the orthographic lexicon. For instance, the output of MACHINE reliance on lexical processing would yield m(a→/ə/). In contrast, a transcription mechanism generates this inconsistent output at a sublexical level that cannot be accurately pronounced by the frequency of sound-letter correspondence (e.g., a→/æ/). The ensuing mismatch between outputs of sublexical and lexical operations leads to conflicts that require additional processing time during writing preparation. Therefore, Chinese participants tend to address conflicts between routes before initiating motor response, while their Spanish counterparts opt for the sublexical route directly, resolving inconsistencies as they arise during real-time processes.

The current results fit with previous L1 studies (e.g., Afonso et al., 2015a; Lau, 2021; Roux & Bonin, 2012), identifying that high-level linguistic variables impact both the central processes of orthographic planning and the peripheral processes of handwritten execution, but that such influence varies with L1 background. Within the context of immediate copying, on the one hand, the P-O consistency effect for the Spanish–English group modulated the kinematics of the movements, as evidenced by shorter inter-letter intervals and writing durations with higher orthographic consistency. This is also true for the writing duration data collected from the spelling-to-dictation task. The persistence of P-O consistency during movement production aligns with findings from L1 Spanish adults (Afonso et al., 2015a, EXP. 2; Afonso et al., 2015b) and children (Afonso et al., 2020; Suárez-Coalla et al., 2020). As stated in the introduction, mapping at all lexical and sublexical levels in Spanish results in the strength of interconnection between phonological and orthographic sublexical units during motor execution. In this sense, Spanish bilinguals might transfer a bias towards phonological mediation in an attempt to activate the corresponding L2 graphemic representations through the application of phoneme-grapheme correspondence. As a result, they slowed the pace of low-level motor processes to accommodate high-order linguistic demands posed by orthographically inconsistent L2 words (e.g., a→/ə/ in the machine). On the other hand, writing durations for the Chinese–English bilinguals were exclusively sensitive to the lexical frequency in motor programming in both tasks. Still, these activation differences that spread into writing execution could be ascribed to the logographic nature of L1 Chinese orthography, leading to heavier processing demand during the storage of low-frequency units in the orthographic output buffer. These findings resulting from between-group comparisons confirm our prediction that the cascading coordination of L2 writing processes would change as a function of L1 orthographic features. Therefore, the processing of the conflicts arising from high-order linguistic variables varies across bilingual groups, in line with prior evidence that the interplay between central and peripheral processes cascades differently for lexical and sublexical levels (e.g., Afonso et al., 2018; Kandel & Perret, 2015; Roux & Bonin, 2012).

https://doi.org/10.1017/S1366728924000087 Published online by Cambridge University Press

Table 2. Immediate Copying Task: Summary of the posterior distribution modeling writing latency, inter-letter interval, and writing duration of critical segments as a function of P-O feedforward consistency and lexical frequency. The table includes posterior medians, the 95% HDI, the percentage of the HDI within the ROPE, and the maximum probability of effect (MPE).

Measures	Parameters	Median	95% HDI	ROPE	MPE
Writing Latency	Intercept	7.26	[7.22, 7.31]	0	1
	Consistency	-0.06	[-0.08, -0.03]	0	1
	Frequency	-0.08	[-0.10, -0.05]	0	1
	Groups	0.12	[0.04, 0.20]	0	1
	Consistency : Frequency	0.01	[-0.01, 0.03]	1	0.74
	Consistency : Groups	-0.09	[-0.12, -0.06]	0	1
	Frequency : Groups	0.01	[-0.03, 0.04]	0.88	0.62
	Consistency : Frequency : Groups	-0.01	[-0.03, 0.01]	0.98	0.78
Inter-letter Interval	Intercept	5.3	[5.24, 5.36]	0	1
	Consistency	-0.06	[-0.09, -0.03]	0	1
	Frequency	-0.01	[-0.04, 0.02]	0.89	0.68
	Groups	0.07	[-0.04, 0.18]	0.18	0.89
	Consistency : Frequency	0.01	[-0.02, 0.04]	0.89	0.75
	Consistency : Groups	0.12	[0.08, 0.16]	0	1
	Frequency : Groups	-0.01	[-0.04, 0.03]	0.85	0.63
	Consistency : Frequency : Groups	0.01	[-0.03, 0.04]	0.91	0.63
Writing Duration	Intercept	7.3	[7.21, 7.38]	0	1
	Consistency	-0.04	[-0.12, 0.04]	0.3	0.86
	Frequency	-0.05	[-0.13, 0.03]	0.24	0.9
	Groups	0.03	[-0.06, 0.12]	0.36	0.75
	Consistency : Frequency	-0.03	[-0.10, 0.03]	0.37	0.84
	Consistency : Groups	0.09	[0.04, 0.15]	0	1
	Frequency : Groups	-0.06	[-0.10, -0.01]	0.08	0.99
	Consistency : Frequency : Groups	0.02	[-0.02, 0.07]	0.55	0.86

One issue pertains to the differing cascading mechanisms that give rise to flexibility in the cascading coordination among bilinguals (Olive, 2014). As stated in the introduction, assuming simultaneous activation of central and peripheral processes is equivalent to assuming their concurrent demands on the limited capacity of the graphemic buffer (i.e., orthographic working memory). In a full-cascade framework, the automatic flows of information between central and peripheral modules occur instantaneously upon the activation of the concept (McClelland, 1979). Limited-cascading models instead posited that parallel processing is not an all-or-nothing occurrence, or that is to say, the amount of overlap is flexible and depends on the cognitive demands of the writing (Dell, 1986; Humphreys et al., 1988; see Olive, 2014). As reviewed earlier, the quantity of linguistic information cascading onto handwritten production varies as a function of age (Afonso et al., 2018; Kandel & Perret, 2015), handwriting skills (Alves et al., 2012; Olive & Kellogg, 2002), developmental disabilities (Afonso et al., 2015b; Suárez-Coalla et al., 2020), and/or the linguistic properties of a target word (Bonin et al., 2012; Roux & Bonin, 2012). Joining these studies, the current results support the limited-cascading account and suggest that the cross-linguistic influence of L1 orthographic backgrounds serves as an additional index of the extent to which L2 high-level linguistic processes operate in parallel. Knowing that the pronunciations assigned to Spanish words can be assembled sublexically, the L2 processing demands associated with P-O conversion for Spanish–English bilinguals outweighed those of lexical frequency during transcription, signifying the simultaneous activation of central orthographic consistency and writing movement. On the contrary, handwriting for Chinese–English bilinguals was equally laborious when transcribing inconsistent L2 words as it was for consistent ones, resulting in the absence of concurrent activation at the sublexical level in both tasks. To avoid exceeding the limited capacity of working memory, Chinese–English bilinguals adopted a sequential strategy to resolve phonological conflicts before the onset of execution. Conversely, the processing difficulties related to spelling low-frequency words carried over to lengthen the writing duration taken on the peripheral processes. Thus, it is proposed that the parallel activation of central and peripheral levels of processing can be achieved when graphomotor output frees up sufficient working memory capacity to enable cascading coordination. Importantly, this dynamic could be influenced by the manner in which bilingual individuals adjust to the various demands of writing in accordance with their L1-specific orthographic characteristics.

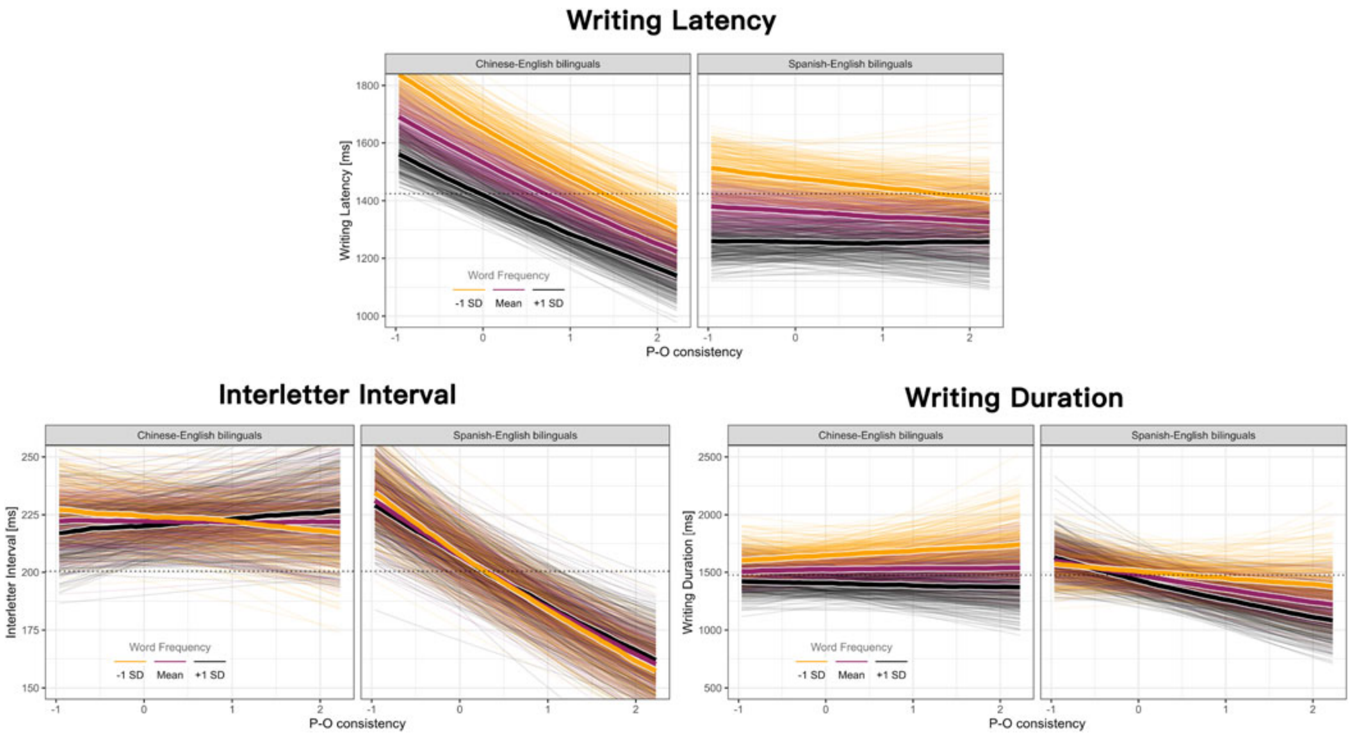

Figure 3. Immediate Copying Task: Probability of writing latency, inter-letter interval and writing duration as a function of P-O consistency while holding lexical frequency constant at −1, 0 and +1 standard deviations from the mean.
Note. Thin lines represent 300 draws from the posterior distribution and indicate uncertainty (95% HDI) around the posterior medians (thick lines). The dotted lines indicate the model intercept.

Also of note is that the primary observation of cross-linguistic variations emerged predominantly in the immediate copying task. In contrast, the bilingual groups resembled the P-O consistency effect on inter-letter interval and the lexical frequency effect on writing durations in the spelling-to-dictation task. This suggests that the predicted pattern of L1-L2 transfer observed here is more likely a by-product of reading, rather than a direct reflection of the writing processes. We emphasize, however, that sensitivity to P-O consistency in the spelling-to-dictation task is prominent for writing durations only within the Spanish group. For this reason, the use of the sublexical procedure proves advantageous for Spanish bilinguals, leading to faster motor execution in comparison to the Chinese group.

In conclusion, the current study illustrates how L1-specific orthographic features affect the structure and functioning of the L2 written production system by modulating the degree of overlap between central and peripheral levels of processing. We propose that the unreliability of sublexical letter-sound conversions in Chinese characters results in the relative automatization of L2 cascading coordination at the lexical level. In contrast, as Spanish orthography presents fewer conflicts between sublexical and lexical routes, the L2 handwriting system for Spanish–English bilinguals tends to favor the assembly of sublexical units to program motor responses. Beyond these specific issues, differences in input modalities also influence the extent to which lexical and sublexical central processes cascade onto the peripheral level of processing. The findings presented here substantiate the emerging trend of bilingualism and advocate for the inclusion of handwritten production as a topic of investigation in bilingualism research. One limitation of this study, however, is the absence of an L1 control group of English writers, making it challenging to discern the implications of orthographic depth or linguistic similarities in our results. Future research is warranted to incorporate both bilingual and monolingual English writers to offer a more comprehensive understanding of L2 writing dynamics.

Acknowledgements. This research was supported by the Spanish Ministry of Science, Innovation PID2020-114246GB-100, "Plan General del Conocimiento", through the project "Orthographic learning in a second language: cross-linguistic and sensorymotor factors" awarded to University of La Laguna. We appreciate the funding from Cajasiete for the first author's international co-supervision Ph.D. scholarship at the University of La Laguna, Spain.

Disclosure statement. No potential conflict of interest was reported by the author(s).

Data availability statement. The data that support the findings of this study are openly available in OSF (osf.io/2wmsq/).

Supplementary Material. For supplementary material accompanying this paper, visit http://doi.org/10.1017/S1366728924000087

For supplementary material accompanying this paper, online supplementary materials S1 include evaluations and scores of the English proficiency and phonological abilities (session 1 and table S1), power estimation considerations (session 2), the list of experimental stimuli and their linguistic properties (table S2). Online supplementary materials S2 provide supporting information for the influence of individual differences in L2 linguistic proficiency on L2 handwritten production.

References

Afonso, O., & Álvarez, C. J. (2019). Constituent frequency effects in the written production of spanish compound words. *Memory & Cognition*, *47*, 1284–1296.

Afonso, O., Álvarez, C. J., & Kandel, S. (2015a). Effects of grapheme-to-phoneme probability on writing durations. *Memory & Cognition*, *43*(4), 579–592.

Afonso, O., Suárez-Coalla, P., & Cuetos, F. (2015b). Spelling impairments in spanish dyslexic adults. *Frontiers in Psychology*, *6*, 466.

Afonso, O., Suárez-Coalla, P., González-Martín, N., & Cuetos, F. (2018). The impact of word frequency on peripheral processes during handwriting: A matter of age. *Quarterly Journal of Experimental Psychology*, *71*(3), 695–703.

Afonso, O., Suárez-Coalla, P., & Cuetos, F. (2020). Writing impairments in spanish children with developmental dyslexia. *Journal of Learning Disabilities*, *53*, 109–119.

Akamatsu, N. (1999). The effects of first language orthographic features on word recognition processing in english as a second language. *Reading and Writing*, *11*(4), 381–403.

Akamatsu, N. (2002). A similarity in word-recognition procedures among second language readers with different first language backgrounds. *Applied Psycholinguistics*, *23*(1), 117–133.

Alvarez, C. J., Cottrell, D., & Afonso, O. (2009). Writing dictated words and picture names: Syllabic boundaries affect execution in spanish. *Applied Psycholinguistics*, *30*(2), 205–223.

Alves, R., Branco, M., Castro, S. L., & Olive, T. (2012). Effects of handwriting skill, output modes, and gender on fourth graders' pauses, language bursts, fluency, and quality. *Past, Present, and Future Contributions of Cognitive Writing Research to Cognitive Psychology*.

Baayen R. H., & Milin P. (2010). Analyzing reaction times. *International Journal of Psychological Research*, *3*(2), 12–28.

Baayen R. H., Davidson D. J., & Bates D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of memory and language*, *59*(4), 390–412.

Basso, A., Taborelli, A., & Vignolo, L. (1978). Dissociated disorders of speaking and writing in aphasia. *Journal of Neurology, Neurosurgery & Psychiatry*, *41*(6), 556–563.

Baxter, D. M., & Warrington, E. K. (1986). Ideational agraphia: A single case study. *Journal of Neurology, Neurosurgery & Psychiatry*, *49*(4), 369–374.

Ben-Yehudah, G., Hirshorn, E. A., Simcox, T., Perfetti, C. A., & Fiez, J. A. (2019). Chinese-english bilinguals transfer L1 lexical reading procedures and holistic orthographic coding to L2 english. *Journal of Neurolinguistics*, *50*, 136–148.

Bonin, P., Peereman, R., & Fayol, M. (2001). Do phonological codes constrain the selection of orthographic codes in written picture naming? *Journal of Memory and Language*, *45*(4), 688–720.

Bonin, P., Roux, S., Barry, C., & Canell, L. (2012). Evidence for a limited-cascading account of written word naming. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(6), 1741.

Bonin, P., Méot, A., Lagarrigue, A., & Roux, S. (2015). Written object naming, spelling to dictation, and immediate copying: Different tasks, different pathways? *Quarterly Journal of Experimental Psychology*, *68*(7), 1268–1294.

Bosse, M.-L., Valdois, S., & Tainturier, M.-J. (2003). Analogy without priming in early spelling development. *Reading and Writing*, *16*(7), 693–716.

Brunswick, N., McCrory, E., Price, C., Frith, C., & Frith, U. (1999). Explicit and implicit processing of words and pseudowords by adult developmental dyslexics: A search for wernicke's wortschatz? *Brain*, *122*(10), 1901–1917.

Bürkner, P.-C. (2017). brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software*, *80*(1), 1–28.

Bürkner, P.-C. (2018). Advanced Bayesian Multilevel Modeling with the R Package brms. *The R Journal*, *10*(1), 395–411.

Chee, Q. W., Chow, K. J., Yap, M. J., & Goh, W. D. (2020). Consistency norms for 37,677 english words. *Behavior Research Methods*, *52*, 2535–2555.

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. New York: Academic Press.

Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In *Attention and performance VI* (pp. 535–555). Routledge.

Costa, A., Miozzo, M., & Caramazza, A. (1999). Lexical selection in bilinguals: Do words in the bilingual's two lexicons compete for selection? *Journal of Memory and Language*, *41*(3), 365–397.

Damian, M. F. (2003). Articulatory duration in single-word speech production. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29* (3), 416.

Damian, M. F., & Stadthagen-Gonzalez, H. (2009). Advance planning of form properties in the written production of single and multiple words. *Language and Cognitive Processes*, *24*(4), 555–579.

Delattre, M., Bonin, P., & Barry, C. (2006). Written spelling to dictation: Sound-to-spelling regularity affects both writing latencies and durations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32* (6), 1330.

de León Rodríguez, D., Buetler, K. A., Eggenberger, N., Laganaro, M., Nyffeler, T., Annoni, J. M., & Müri, R. M. (2016). The impact of language opacity and proficiency on reading strategies in bilinguals: An eye movement study. *Frontiers in psychology*, *7*, 649.

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review*, *93*(3), 283.

Dijkstra, T., & Van Heuven, W. J. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism: Language and Cognition*, *5*(3), 175–197.

Dijkstra, T., Heuven, W. J. B. V., & Grainger, J. (1998). Simulating cross-language competition with the bilingual interactive activation model. *Psychologica Belgica*, *38*, 177–196.

Ellis, A. W. (1979). Cd slips of the pen. *Visible Language*, *13*(3), 265–282.

Fernando, C. V. (2000). Psicología de la escritura, diagnóstico y tratamiento de los trastornos de escritura. CISS praxis educación. *Monografías Escuela Española*.

Folk, J. R., Rapp, B., & Goldrick, M. (2002). The interaction of lexical and sublexical information in spelling: What's the point? *Cognitive Neuropsychology*, *19*(7), 653–671.

Frost, R., Katz, L., & Bentin, S. (1987). Strategies for visual word recognition and orthographical depth: A multilingual comparison. *Journal of Experimental Psychology: Human Perception and Performance*, *13*(1), 104.

Gelman, A., Simpson, D., & Betancourt, M. (2017). The prior can often only be understood in the context of the likelihood. *Entropy*, *19*(10), 1–13.

Geschwind, N. (1974). Problems in the anatomical understanding of the aphasias. In *Selected papers on language and the brain* (pp. 431–451). Springer.

Guinet, E., & Kandel, S. (2010). Ductus: A software package for the study of handwriting production. *Behavior Research Methods*, *42*(1), 326–332.

Hamada, M., & Koda, K. (2008). Influence of first language orthographic experience on second language decoding and word learning. *Language Learning*, *58*(1), 1–31.

Hamada, M., & Koda, K. (2010). The role of phonological decoding in second language word-meaning inference. *Applied Linguistics*, *31*(4), 513–531.

Hamada, M., & Koda, K. (2011). Similarity and difference in learning L2 word-form. *System*, *39*(4), 500–509.

Houghton, G., & Zorzi, M. (2003). Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology*, *20*(2), 115–162.

Humphreys, G. W., Riddoch, M. J., & Quinlan, P. T. (1988). Cascade processes in picture identification. *Cognitive Neuropsychology*, *5*(1), 67–104.

Jared, D. (1997). Spelling–sound consistency affects the naming of high-frequency words. *Journal of Memory and Language*, *36*(4), 505–529.

Jared, D., McRae, K., & Seidenberg, M. S. (1990). The basis of consistency effects in word naming. *Journal of Memory and Language*, *29*(6), 687–715.

Kandel, S., & Perret, C. (2015). How does the interaction between spelling and motor processes build up during writing acquisition? *Cognition*, *136*, 325–336.

Kandel, S., & Spinelli, E. (2010). Processing complex graphemes in handwriting production. *Memory & Cognition*, *38*, 762–770.

Kandel, S., & Valdois, S. (2006). French and spanish-speaking children use different visual and motor units during spelling acquisition. *Language and Cognitive Processes*, *21*(5), 531–561.

Kandel, S., Peereman, R., Grosjacques, G., & Fayol, M. (2011). For a psycholinguistic model of handwriting production: Testing the syllable-bigram controversy. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(4), 1310.

Kandel, S., Peereman, R., & Ghimenton, A. (2013). Further evidence for the interaction of central and peripheral processes: The impact of double letters in writing english words. *Frontiers in Psychology*, *4*, 729.

Kandel, S., Peereman, R., Ghimenton, A., & Perret, C. (2019). Letter coding affects movement production in word writing: An english–italian cross-linguistic study. *Reading and Writing*, *32*(1), 95–114.
Keuleers, E. (2013). *Vwr: Useful functions for visual word recognition research.* https://CRAN.R-project.org/package=vwr
Keuleers, E., Lacey, P., Rastle, K., & Brysbaert, M. (2012). The british lexicon project: Lexical decision data for 28,730 monosyllabic and disyllabic english words. *Behavior Research Methods*, *44*, 287–304.
Koda, K. (2007). Reading and language learning: Crosslinguistic constraints on second language reading development. *Language Learning*.
Koda, K. (2008). Impacts of prior literacy experience on second language learning to read. In *Learning to read across languages* (pp. 80–108). Routledge.
Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations. *Journal of Memory and Language*, *33*(2), 149–174.
Kroll, J. F., & Tokowicz, N. (2005). *Models of bilingual representation and processing: Looking back and to the future.* Oxford University Press.
Kroll, J. F., Van Hell, J. G., Tokowicz, N., & Green, D. W. (2010). The revised hierarchical model: A critical review and assessment. *Bilingualism: Language and Cognition*, *13*(3), 373–381.
Kruschke, J. K. (2018). Rejecting or accepting parameter values in Bayesian estimation. *Advances in Methods and Practices in Psychological Science*, *1* (2), 270–280.
Lacruz, I., & Folk, J. R. (2004). Feedforward and feedback consistency effects for high-and low-frequency words in lexical decision and naming. *The Quarterly Journal of Experimental Psychology Section A*, *57*(7), 1261–1284.
Lallier, M., & Carreiras, M. (2018). Cross-linguistic transfer in bilinguals reading in two alphabetic orthographies: The grain size accommodation hypothesis. *Psychonomic bulletin & review*, *25*, 386-401.
Lambert, E., Alamargot, D., Larocque, D., & Caporossi, G. (2011). Dynamics of the spelling process during a copy task: Effects of regularity and frequency. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *65*(3), 141.
Lau, D. K. Y. (2019). Grain size units of chinese handwriting: Development and disorder. *Clinical Linguistics and Phonetics*, *33*, 869–884.
Lau, D. K. Y. (2021). The dual-route account of writing-to-dictation in chinese: A short report. *Language and Speech*, *64*(4), 790–803.
Lemhöfer, K., & Broersma, M. (2012). Introducing LexTALE: A quick and valid lexical test for advanced learners of english. *Behavior Research Methods*, *44*, 325–343.
Li, P., Zhang, F., Yu, A., & Zhao, X. (2020). Language History Questionnaire (LHQ3): An enhanced tool for assessing multilingual experience. *Bilingualism: Language and Cognition*, *23*(5), 938-944.
Lorenz, A., Zwitserlood, P., Bürki, A., Regel, S., Ouyang, G., & Rahman, R. A. (2021). Morphological facilitation and semantic interference in compound production: An ERP study. *Cognition*, *209*, 104518.
Maxwell S. E., Kelley K., & Rausch J. R. (2008). Sample size planning for statistical power and accuracy in parameter estimation. *Annual Review of Psychologyl*, *59*, 537–563.
McClelland, J. L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. *Psychological Review*, *86*(4), 287.
Meyer, A. S., Roelofs, A., & Levelt, W. J. (2003). Word length effects in object naming: The role of a response criterion. *Journal of Memory and Language*, *48*(1), 131–147.
Miceli, G., & Miceli, G. (1997). Semantic errors as neuropsychological evidence for the independence and the interaction of orthographic and phonological word forms. *Language and Cognitive Processes*, *12*(5-6), 733–764.
Mokhtari, K., & Reichard, C. A. (2002). Assessing students' metacognitive awareness of reading strategies. *Journal of Educational Psychology*, *94* (2), 249.
Olive, T. (2014). Toward a parallel and cascading model of the writing system: A review of research on writing processes coordination. *Journal of Writing Research*, *6*(2), 173–194.
Olive, T., & Kellogg, R. T. (2002). Concurrent activation of high-and low-level production processes in written composition. *Memory & Cognition*, *30*(4), 594–600.
Oppenheim G. M. (2018). The paca that roared: Immediate cumulative semanticinterference among newly acquired words. *Cognition*, *177*, 21–29.
Perry, C., & Ziegler, J. C. (2002). Cross-language computational investigation of the length effect in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(4), 990.
Planton, S., Jucla, M., Roux, F.-E., & Démonet, J.-F. (2013). The "handwriting brain": A meta-analysis of neuroimaging studies of motor versus orthographic processes. *Cortex*, *49*(10), 2772–2787.
Purcell, J. J., Turkeltaub, P. E., Eden, G. F., & Rapp, B. (2011). Examining the central and peripheral processes of written word production through meta-analysis. *Frontiers in Psychology*, *2*, 239.
Qu, Q., Damian, M. F., Zhang, Q., & Zhu, X. (2011). Phonology contributes to writing: Evidence from written word production in a nonalphabetic script. *Psychological Science*, *22*(9), 1107–1112.
Rabe, M. M., Vasishth, S., Hohenstein, S., Kliegl, R., & Schad, D. J. (2020). Hypr: An r package for hypothesis-driven contrast coding. *Journal of Open Source Software*, *5*(48), 2134.
Rapp, B., Benzing, L., & Caramazza, A. (1997). The autonomy of lexical orthography. *Cognitive Neuropsychology*, *14*(1), 71–104.
R Core Team. (2022). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing. https://www.R-project.org/
Roux, S., & Bonin, P. (2012). Cascaded processing in written naming: Evidence from the picture–picture interference paradigm. *Language and Cognitive Processes*, *27*(5), 734–769.
Roux, S., McKeeff, T. J., Grosjacques, G., Afonso, O., & Kandel, S. (2013). The interaction between central and peripheral processes in handwriting production. *Cognition*, *127*(2), 235–241.
Rumelhart, D. E., & Norman, D. A. (1982). Simulating a skilled typist: A study of skilled cognitive-motor performance. *Cognitive Science*, *6*(1), 1–36.
Seidenberg, M. S. (1985). The time course of phonological code activation in two writing systems. *Cognition*, *19*(1), 1–30.
Share, D. L. (2008). On the Anglocentricities of current reading research and practice: The perils of overreliance on an "outlier" orthography. *Psychological Bulletin*, *134*(4), 584–615. https://doi.org/10.1037/0033-2909.134.4.584
Stan Development Team. (2018). *Stan modeling language users guide and reference manual* (Version 2.18.0) [Computer software]. Stan Development Team. http://mc-stan.org
Steacy, L. M., Compton, D. L., Petscher, Y., Elliott, J. D., Smith, K., Rueckl, J. G., Sawi, O., Frost, S. J., & Pugh, K. R. (2019). Development and prediction of context-dependent vowel pronunciation in elementary readers. *Scientific Studies of Reading*, *23*(1), 49–63.
Suárez-Coalla, P., González-Martín, N., & Cuetos, F. (2018). Word writing in spanish-speaking children: Central and peripheral processes. *Acta Psychologica*, *191*, 201–209.
Suárez-Coalla, P., Villanueva, N., González-Pumariega, S., & González-Nosti, M. (2016). Spelling difficulties in spanish-speaking children with dyslexia/ dificultades de escritura en niños españoles con dislexia. *Infancia y Aprendizaje*, *39*(2), 275–311.
Suárez-Coalla, P., Afonso, O., Martínez-García, C., & Cuetos, F. (2020). Dynamics of sentence handwriting in dyslexia: The impact of frequency and consistency. *Frontiers in Psychology*, *11*, 319.
Tabachnick, B. G., Fidell, L. S., & Ullman, J. B. (2013). *Using Multivariate Statistics*, Vol. *6*. Boston, MA: pearson, pp. 497–516.
Tainturier, M.-J., & Rapp, B. (2001). The spelling process. *The Handbook of Cognitive Neuropsychology: What Deficits Reveal about the Human Mind*, 263–289.
Tainturier, M.-J., Bosse, M.-L., Roberts, D. J., Valdois, S., & Rapp, B. (2013). Lexical neighborhood effects in pseudoword spelling. *Frontiers in Psychology*, *4*, 862.
Treiman, R. (2018). Statistical learning and spelling. *Language, Speech, and Hearing Services in Schools*, *49*(3S), 644–652.
Van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science*, *10*(2-3), 165–191.
Van Heuven, W. J., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). SUBTLEX-UK: A new and improved word frequency database for british english. *Quarterly Journal of Experimental Psychology*, *67*(6), 1176–1190.
Wagner, R. K., Torgesen, J. K., Rashotte, C. A., & Pearson, N. A. (1999). *Comprehensive test of phonological processing: CTOPP.* Pro-ed Austin, TX.
Wang, M., & Koda, K. (2005). Commonalities and differences in word identification skills among learners of english as a second language. *Language Learning*, *55*(1), 71–98.

https://doi.org/10.1017/S1366728924000087 Published online by Cambridge University Press

Wang, M., Koda, K., & Perfetti, C. A. (2003). Alphabetic and nonalphabetic L1 effects in english word identification: A comparison of korean and chinese english L2 learners. *Cognition*, *87*(2), 129–149.
Wang, R., Huang, S., Zhou, Y., & Cai, Z. G. (2020). Chinese character handwriting: A large-scale behavioral study and a database. *Behavior Research Methods*, *52*(1), 82–96.
Weingarten, R. (2005). Subsyllabic units in written word production. *Written Language & Literacy*, *8*(1), 43–61.
Yarkoni, T., Balota, D., & Yap, M. (2008). Moving beyond coltheart's n: A new measure of orthographic similarity. *Psychonomic Bulletin & Review*, *15*(5), 971–979.
Zhang, Q., & Feng, C. (2017). The interaction between central and peripheral processing in chinese handwritten production: Evidence from the effect of lexicality and radical complexity. *Frontiers in Psychology*, *8*, 334.
Zhang, Q., & Wang, C. (2015). Phonology is not accessed earlier than orthography in chinese written production: Evidence for the orthography autonomy hypothesis. *Frontiers in Psychology*, *6*, 448.
Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, *131*(1), 3.
Ziegler, J. C., Perry, C., Jacobs, A. M., & Braun, M. (2001). Identical words are read differently in different languages. *Psychological Science*, *12*(5), 379–384.