Direct Retrieval of Orthographic Representations in Chinese Handwritten Production: Evidence from a Dynamic Causal Modeling Study

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Abstract

■ This present study identified an optimal model representing the relationship between orthography and phonology in Chinese handwritten production using dynamic causal modeling, and further explored how this model was modulated by word frequency and syllable frequency. Each model contained five volumes of interest in the left hemisphere (angular gyrus [AG], inferior frontal gyrus [IFG], middle frontal gyrus [MFG], superior frontal gyrus [SFG], and supramarginal gyrus [SMG]), with the IFG as the driven input area. Results showed the superiority of a model in which both the MFG and the AG connected with the IFG, supporting the orthography autonomy hypothesis. Word frequency modulated the AG → SFG connection (information flow from the orthographic lexicon to the orthographic buffer), and syllable frequency affected the IFG → MFG connection (information transmission from the semantic system to the phonological lexicon). This study thus provides new insights into the connectivity architecture of neural substrates involved in writing. ■

INTRODUCTION

Written language production requires several interactive cognitive processes that have been depicted in various models (e.g., Beeson & Rapcsak, 2002; Bonin, Peereman, & Fayol, 2001; Rapp & Caramazza, 1997; Roeltgen & Heilman, 1985). For instance, Figure 1 illustrates a working model of written picture naming (Bonin et al., 2001): When a picture is presented, individuals identify the object first and activate its semantic representations that then flow into an orthographic lexicon and a phonological lexicon in parallel. Next, activated orthographic representations propagate to a graphemic buffer (or an orthographic buffer in Chinese; see Han, Zhang, Shu, & Bi, 2007), whereas activated phonological representations flow into the graphemic buffer either via a lexical route (link A in Figure 1) or via a sublexical route (i.e., phonology-to-grapheme/orthography conversion; links B and D in Figure 1). Finally, the orthographic representations that maintained active in the graphemic/orthographic buffer are translated into writing by selecting allographs, and planning and executing motor programs. Although these cognitive processes are highly interactive, an important distinction has been made between the central and peripheral components (see Figure 1). In the following section, we first review two types of debatable hypotheses in writing literature on the relationship of phonology to orthography and then present a relevant study on Chinese written word production and also introduce the effects of word frequency and syllable frequency. After this, we move to neuroimaging studies on written language production, then to the dynamic causal modeling (DCM) approach, and finally to the purposes of the current study.

A central theoretical debate in written language production is whether the retrieval of orthography is constrained by prior phonological codes. The *obligatory phonological mediation hypothesis* (Luria, 1970; Geschwind, 1969) assumes that the processing of orthographic representations entirely depends on the prior retrieval of phonological codes. This has been supported by the observation that speaking precedes writing ontogenetically and phylogenetically (e.g., Scinto, 1986), by certain types of spelling errors such as phonologically plausible nonwords (e.g., "*dearth*" spelled as "*dirth*") and homophone substitutions (e.g., "*there*" spelled as "*their*"; Aitchison & Todd, 1982).

However, the obligatory phonological mediation hypothesis (Luria, 1970; Geschwind, 1969) has been challenged because neuropsychological studies have demonstrated a clear dissociation between spoken and written language production, as they found that patients with acquired agraphia were able to write but unable to speak because of damage to the phonological lexicon (e.g., Bub & Kertesz, 1982), or patients produced inconsistent written and spoken responses for the same picture (e.g., wrote "*saw*" but said "*pincers*" for the picture "*pliers*"; Alario, Schiller, Domoto-Reilly, & Caramazza, 2003; Miceli, Benvegnù, Capasso, & Caramazza, 1997). These findings motivated the *orthographic autonomy hypothesis* (Miceli et al., 1997; Rapp, Benzing, & Caramazza, 1997; Rapp & Caramazza, 1997), which claims that orthographic

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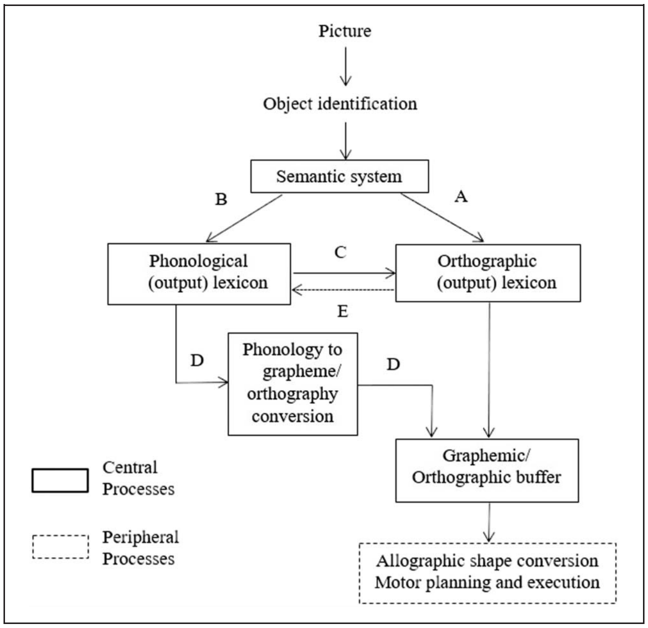

Figure 1. A working model of written picture naming (Adapted from Bonin et al., 2001). Link A represents the lexical route. Links B and D represent the sublexical route. Links C and E indicate the bi-directional link between the two lexicons.

representations can be accessed from the semantic system directly in writing, without phonological mediation.

It is worth noticing that the orthographic autonomy hypothesis (Miceli et al., 1997; Rapp & Caramazza, 1997; Rapp et al., 1997) does not rule out the possibility that phonological representations contribute to the retrieval of orthographic information. Miceli and colleagues (1997) thus distinguished between a weak and a strong version of the orthographic autonomy hypotheses: The weak orthographic autonomy hypothesis assumes that the representations in the phonological and orthographic lexicons can be directly activated from the semantic system (links A and B in Figure 1) and then map onto each other through a lexical route (link C in Figure 1; e.g., Patterson & Shewell, 1987; Allport & Funnell, 1981). Damian, Dorjee, and Stadthagen-Gonzalez (2011) have further proposed that there should also be a backward link from the orthographic lexicon to the phonological lexicon (link E in Figure 1). By contrast, the strong orthographic autonomy hypothesis denies the direct lexical route (links C and E in Figure 1) between the two lexicons and stipulates that phonological representations contribute to the access of orthography only via a sublexical route of phonology-to-grapheme/orthography conversion (link D in Figure 1).

Previous studies on unimpaired individuals, with chronometric and electrophysiological techniques, have painted a mixed picture of the relationship between phonology and orthography in writing. For example, some of them have found that phonological codes constrain the retrieval of orthography via the lexical route and/or the sublexical route of phonology-to-grapheme/orthography conversion (e.g., in Spanish, Afonso & Álvarez, 2011; in French, Bonin, et al., 2001; in Chinese, Qu & Damian, 2020; Damian & Qu, 2013), whereas others have shown that orthographic representations can be accessed directly from the semantic system (e.g., in French, Bonin, Fayol, & Peereman, 1998; in Chinese, Zhang & Wang, 2014). The evidence from these studies is inconclusive; more research is thus needed to examine the extent to which the retrieval of orthography in writing is autonomous from, or dependent on, prior phonological codes.

Unlike alphabetic languages (e.g., English) in which the phonology–orthography correspondences are transparent, Chinese is a language with nontransparent mapping between orthography and phonology. This means the orthography and phonology in Chinese are largely dissociated, resulting that the orthographic and phonological effects can be separated from one another with an appropriate manipulation (see also Zhang & Wang, 2014). This characteristic makes Chinese an ideal writing system to explore whether orthographic information can be accessed from the semantic system directly or constrained by phonological codes. For instance, Zhang and Wang (2014) investigated how phonological processes affected the retrieval of orthography by manipulating the syllable frequency (high, low) and word frequency (high, low) of pictures in a Chinese written picture naming task. Word frequency effect refers to the finding that picture names with a low word frequency are produced slower than those with a high word frequency in both spoken and written language production (Baus, Strijkers, & Costa, 2013; Wingfield, 1968; Oldfield & Wingfield, 1965). This effect was assumed to index the robustness of the orthographic lexicon (e.g., Chen, Chang, Chen, Lin, & Wu, 2016; Rapp & Dufor, 2011; Goodman & Caramazza, 1986). Syllable frequency effect refers to the finding that picture names with a low-syllable frequency are produced slower than those with a high-syllable frequency (Levelt, Roelofs, & Meyer, 1999; Levelt & Wheeldon, 1994). This effect is assumed to occur at the phonological encoding stage in Chinese (O'Seaghdha, Chen, & Chen, 2010). They found no interaction between the word frequency and syllable frequency, which suggests that orthographic processing is independent of phonological encoding in Chinese handwritten production, supporting the orthographic autonomy hypothesis (Miceli et al., 1997; Rapp & Caramazza, 1997; Rapp et al., 1997).

However, the basic assumption, the effects of word frequency and syllable frequency index on the orthographic and phonological processes, respectively, is somewhat problematic. This is because the exact cognitive processes that the word frequency and syllable frequency affect in written language production remain controversial (see also Wang & Zhang, 2021; Bonin, Laroche, & Perret, 2016; Qu, Zhang, & Damian, 2016). The dominant view claims that the word frequency effect occurs mainly at the processing level of the orthographic lexicon (e.g., Chen et al., 2016; Rapp & Dufor, 2011; Goodman & Caramazza, 1986), but some studies have shown that the word frequency effect may also arise at the lexical-semantic access in written language production (e.g., Qu et al., 2016; Almeida, Knobel, Finkbeiner, & Caramazza, 2007; Alario, Costa, & Caramazza, 2002; Bonin & Fayol, 2002). It has been assumed that syllable frequency affects early phonological encoding in Chinese written production (O'Seaghdha et al., 2010), but direct empirical evidence for locating the syllable frequency effect is scarce. Thus, the present study employed the DCM (Friston, Harrison, & Penny, 2003) approach to investigate the role of phonology in orthographic output in Chinese writing. Before we move on to the details of the DCM approach, we review the neural substrates associated with certain processing components involved in writing.

An increasing number of neuroimaging research has focused on identifying specialized functional brain regions associated with the processing components involved in writing (e.g., Yang et al., 2018; Chen et al., 2016; Segal & Petrides, 2012; Purcell, Turkeltaub, Eden, & Rapp, 2011; Rapp & Dufor, 2011; Harrington, Farias, Davis, & Buonocore, 2007; Beeson et al., 2003). In terms of orthographic processes, the left posterior inferior temporal gyrus (Brodmann area [BA] 37) and mid-fusiform gyrus (BA 37) are known to be responsible for storing orthographic representations in the orthographic lexicon (e.g., Beeson et al., 2003; Soma, Sugishita, Kitamura, Maruyama, & Imanaga, 1989; Kawahata, Nagata, & Shishido, 1988). The left angular gyrus (AG; BA 39) is also shown to be associated with the storage of orthographic knowledge in the lexicon (e.g., Segal & Petrides, 2012, 2013; Joubert et al., 2004; Roeltgen & Heilman, 1984; Beauvois & Dérouesné, 1981). The left superior frontal gyrus (SFG) is primarily associated with the graphemic/orthographic buffer that temporally holds graphemic/orthographic representations before the execution of written responses (e.g., Rapp & Dufor, 2011; Cloutman et al., 2009).

Phonological processing in writing is mainly associated with activation in the left temporoparietal cortex including the superior temporal gyrus and supramarginal gyrus (SMG; BA 40; e.g., Sugihara, Kaminaga, & Sugishita, 2006; Roeltgen, Sevush, & Heilman, 1983; Beauvois & Dérouesné, 1981). The SMG (BA 40) is considered to be related to the sublexical processing of phonology-to-grapheme/orthography conversion involved in writing (e.g., Sugihara et al., 2006). A large-scale meta-analysis study on brain–language relationships by Vigneau and colleagues (2006) has identified a specific phonological processing area (i.e., Rolandic sulcus located in the middle frontal gyrus [MFG]) among 129 scientific studies with phonological tasks, such as repeat or articulate syllables, and read/listen or attend to syllables/letters. Consistent with this, some studies on Chinese processing have shown that the left MFG is involved in phonological processing (e.g., Tan, Laird, Li, & Fox, 2005; Tan et al., 2003). In addition, the posterior portions of the left inferior frontal gyrus (IFG) are also functionally specific for phonological processing in language production (e.g., Jobard, Crivello, & Tzourio-Mazoyer, 2003; Klaus & Hartwigsen, 2019).

The left IFG (distinct from the portions of the left IFG associated with phonological processing) has been repeatedly identified for semantic processing in language production (e.g., Heim, Eickhoff, & Amunts, 2009; Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Miceli et al., 2002). Consistent with this, a specific semantic processing area (i.e., the left precentral gyrus/F3op junction) identified in the meta-analysis study on brain–language relationships (Vigneau et al., 2006) is also located at the upper part of the left IFG at the junction with the precentral gyrus.

The functional segregation of different brain areas subserving writing has been investigated, but it still remains largely unknown as to how these defined brain regions cooperate and interacted with one another in a neuronal network to support writing. A few studies have used functional connectivity approaches to explore how writing-related brain areas are functionally integrated and to demonstrate neural synchronization among the cognitive, linguistic, and perceptual-motor networks supporting writing (e.g., Yang et al., 2019; Segal & Petrides, 2012). However, the correlational approaches cannot reveal the causal influence of one neural system on another (Friston, 2011) and thus could not provide direct evidence for the debate on whether the retrieval of orthography is constrained by prior phonological codes in writing. To overcome this limitation, the present study employed the DCM method (Friston et al., 2003) to investigate how the interaction and integration of brain regions support handwritten production in Chinese.

DCM is a well-established approach to identifying the effective connectivity between brain regions. It is an approach to characterize functional integration in the brain, but it is different from functional connectivity, which is inferred based on correlations among measurements of neuronal activity (Friston, 2011). A dynamic causal model is a neurodynamic model that depicts the brain as a nonlinear, but deterministic system, in which the activity in one area causes a change of activity in another area (see Penny et al., 2010; Stephan, Weiskopf, Drysdale, Robinson, & Friston, 2007; Friston et al., 2003, for more details). DCM estimates the temporal precedence of one brain region over another and then assesses how changes in multiple regions influence each other linearly and nonlinearly across time, and how those neural interactions are modulated by external perturbations (i.e., driving inputs eliciting responses on specific network nodes, or modulatory inputs exerting the influence through modulation of the coupling among nodes). This is accomplished by modeling time-varying hidden parameters that influence the transformation of neuronal activity into a hemodynamic response. Thereby, DCM can be implemented to examine effective connectivity that reflects the directed causal influence between brain regions under given experimental conditions (Friston, 2011). The DCM approach requires a hypothesis-driven definition of competing network models that reflect different assumptions about how inter-regional interactions support a particular task. These models are then compared with each other based on the evidence from the present data to identify an optimal dynamic network model subserving a particular task. These features of the DCM, therefore, make it a better approach, relative to the functional connectivity methods, to distinguish the alternative hypotheses regarding the contribution of phonology to the retrieval of orthography in written language production, and also to identify the exact loci of the effects of word frequency and syllable frequency.

Overall, the present study first explored how phonological codes affected the retrieval of orthography in Chinese handwritten production by comparing four competing dynamic causal models that varied concerning the influences of phonology on the retrieval of orthography (see Analysis 1 in the Methods section and Figure 2 for details of each model), which would contribute to the long-standing debate about the role of phonology in orthographic output in writing. After determining the optimal dynamic network model supporting writing, we further identified the exact cognitive processes of the effects of word frequency and syllable frequency. As mentioned earlier, word frequency may affect processing levels of the lexical-semantic access and/or orthographic lexicon (e.g., Chen et al., 2016; Qu et al., 2016; Rapp & Dufor, 2011; Goodman & Caramazza, 1986). Given that the processes involved in writing are highly interactive, we also performed a completely exploratory investigation on the modulations by word frequency. That is, we reasoned that word frequency might also modulate the information transmission associated with the lexical-semantic access and orthographic lexicon. We thus compared six competing dynamic causal models that share intrinsic connections with the optimal model but with varied modulatory effects (on certain processing components and/or transmission) of word frequency (see Analysis 2.1 in the Methods section and Figure 3 for details). We also compared six dynamic causal models with different modulatory effects of syllable frequency (see Analysis 2.2 in the Methods section and Figure 4 for details), based on the proposal that syllable frequency influences the stage of the phonological lexicon (O'Seaghdha et al., 2010), and also based on an exploratory assumption that syllable frequency may also affect the information transmission linking to the phonological lexicon. The hypotheses of each dynamic causal model test are listed in Table 1.

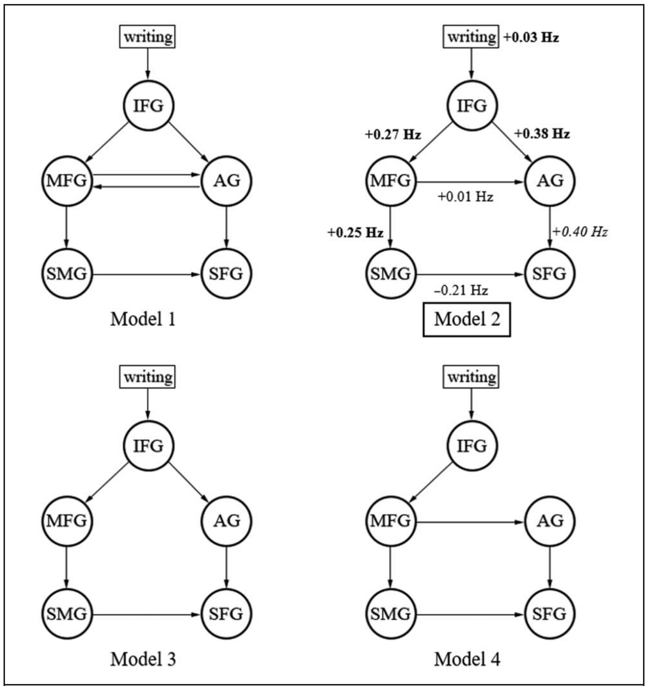

Figure 2. Four dynamic causal models reflect the relationship between phonology and orthography in Chinese handwritten production. Model 2 is the optimal model, in which numbers alongside regions or connections indicate their average parameter estimates. **Bold** print indicates that values are significantly different from zero, italic print indicates that the values are marginally significantly different from zero, and regular print represents that values are not significantly different from zero. AG = angular gyrus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; SFG = superior frontal gyrus; SMG = supramarginal gyrus. All brain regions are located in the left hemisphere. Writing refers to the writing task.

METHODS

Participants

The data of 14 participants (7 male participants; mean age = 21.3 years old) from our previous study (23 participants; He, Brehm, & Zhang, 2022) were used for the DCM analysis. All participants were healthy, right-handed, native Mandarin Chinese speakers (11 male participants; mean age = 22 years old) from Renmin University of China. They reported normal or corrected-to-normal vision, normal reading and writing abilities, no hearing impairments, and history of neurological or psychiatric disorders. They also signed written informed consent and received a payment of ¥160 for their participation. Two participants were discarded because of excessive head motions (participants were excluded if their head motion in the vector of the x, y, or z direction was more than one voxel [3 mm]), and seven participants were excluded from the original sample because they failed to have their activation maximum in the five volumes of interest (VOIs) used to build dynamic causal models (see DCM Analysis for details) within a predefined search radius of 16 mm at a threshold of $p < .05$ (uncorrected). The data from the remaining 14 participants were used for DCM analysis. This sample size seems appropriate for our study because it is similar to that used in most DCM studies on language processing (e.g., 15 participants for the lexical decision study by Heim, Eickhoff, Ischebeck, et al., 2009; 14 participants for the speech perception study by Osnes, Hugdahl, & Specht, 2011; 17 participants for visual word recognition study by Xu, Wang, Chen, Fox, & Tan, 2015). The study

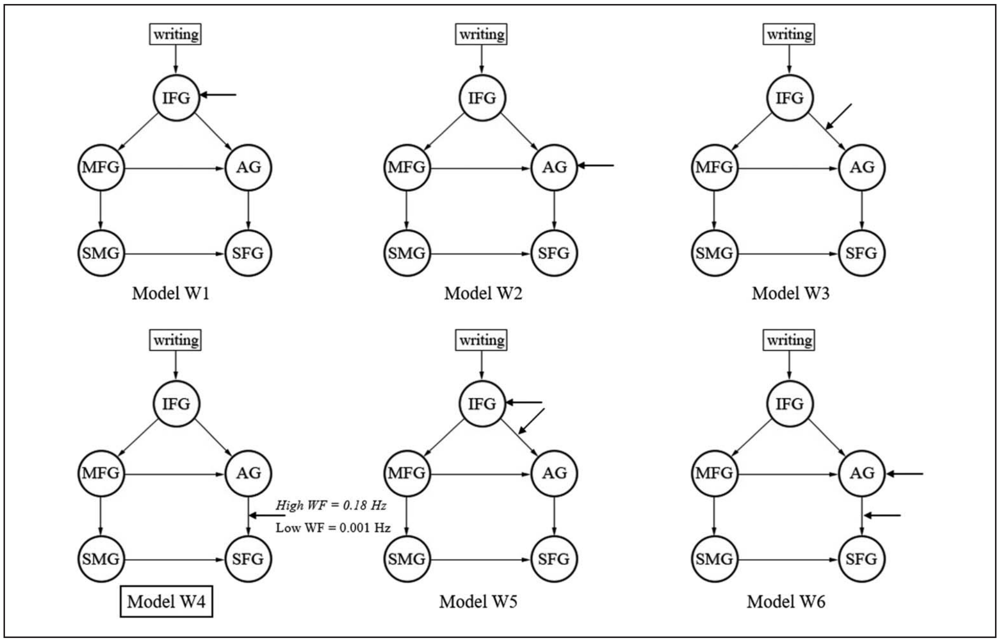

Figure 3. Six dynamic causal models representing possible modulations of word frequency (WF). Model W4 is the optimal model, in which numbers alongside the AG → SFG connection indicate their average parameter estimates. Italic print indicates that the value is marginally significantly different from zero, and regular print represents that the value is not significantly different from zero. AG = angular gyrus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; SFG = superior frontal gyrus; SMG = supramarginal gyrus. All brain regions are located in the left hemisphere. Writing refers to the writing task.

was approved by the ethics review board in the Institute of Psychology, Chinese Academy Sciences.

Stimuli

Sixty pictures (see https://osf.io/8wa2s/) with monosyllabic names (see Appendix A, Table A1) were selected from the database of black-and-white line drawings (Zhang & Yang, 2003) with language norms in Standard Mandarin Chinese. For the picture names, word frequencies were obtained from the Chinese Frequency Dictionary (Beijing Language Institute, 1986), and syllable frequencies were calculated by summing the word frequencies of one syllable without counting tones (see He et al., 2022, for more details). The frequency measurements we employed have been widely used in previous studies on written language production in Chinese (e.g., Wang, Jiang, & Zhang, 2023; Zhang & Wang, 2014). Of the picture names, 30 of the picture names had high word frequency (≥ 130 per/million) and the other 30 had low word frequency (≤ 47 per/million). For each set of picture names with high or low word frequency, half had a high-syllable frequency (≥ 2558 per/million) and the other half had a low-syllable frequency (≤ 1479 per/million). Word frequency (high,

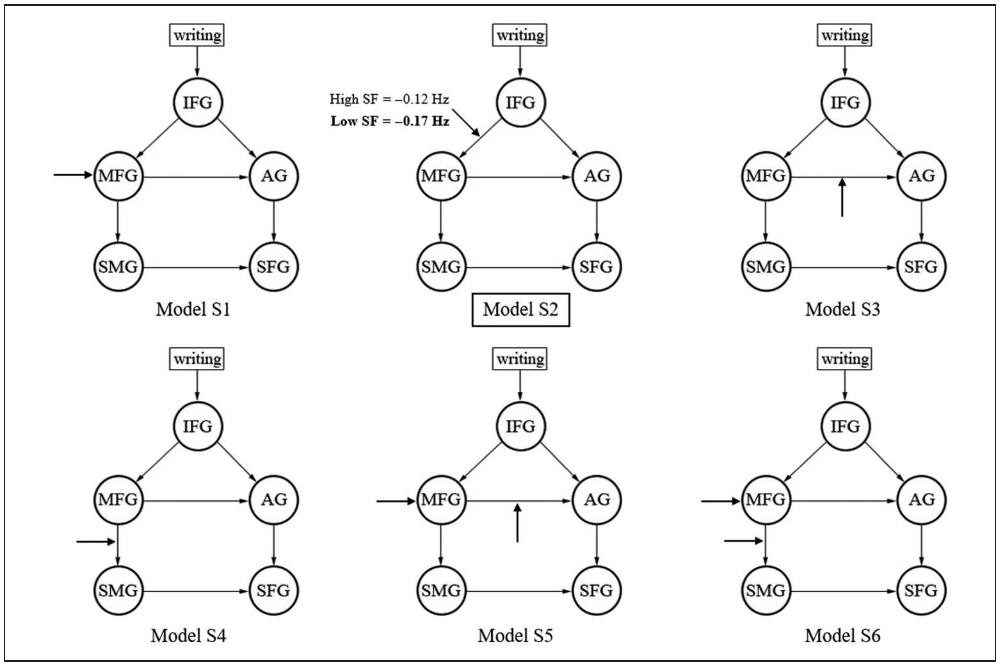

Figure 4. Six dynamic causal models representing possible modulations of syllable frequency (SF). Model S2 is the optimal model, in which numbers alongside the IFG → MFG connection indicate their average parameter estimates. **Bold** print indicates that the value is significantly different from zero, and regular print represents that the value is not significantly different from zero. AG = angular gyrus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; SFG = superior frontal gyrus; SMG = supramarginal gyrus. All brain regions are located in the left hemisphere. Writing refers to the writing task.

Table 1. Hypotheses Each Model Tests and the Corresponding Connectivities/Modulations in the Present Study

	Hypotheses	*Connectivities*
Analysis 1. Models reflecting the relationship between phonology and orthography		
Model 1	Weak orthographic autonomy hypothesis with a bidirectional lexical route	IFG → AG
		IFG → MFG ↔ AG
Model 2	Weak orthographic autonomy hypothesis with a unidirectional lexical route	IFG → AG
		IFG → MFG → AG
Model 3	Strong orthographic autonomy hypothesis without a bidirectional lexical route	IFG → AG
		IFG → MFG
Model 4	Obligatory phonological mediation hypothesis	IFG → MFG → AG

	Hypotheses	*Modulations*
Analysis 2.1. Models representing possible modulations of word frequency		
Model W1	Semantic system	IFG
Model W2	Orthographic lexicon	AG
Model W3	Information transmission from the semantic system to the orthographic lexicon	IFG → AG
Model W4	Information transmission from the orthographic lexicon to the orthographic buffer	AG → SFG
Model W5	Semantic system; information transmission from the semantic system to the orthographic lexicon	IFG; IFG → AG
Model W6	Orthographic lexicon; information transmission from the orthographic lexicon to the orthographic buffer	AG; AG → SFG
Analysis 2.2. Models representing possible modulations of syllable frequency		
Model S1	Phonological lexicon	MFG
Model S2	Information transmission from the semantic system to the phonological lexicon	IFG → MFG
Model S3	Information transmission from the phonological lexicon to the orthographic lexicon	MFG → AG
Model S4	Information transmission from the phonological lexicon to the phonology-to-orthography conversion	MFG → SMG
Model S5	Phonological lexicon; Information transmission from the phonological lexicon to the orthographic lexicon	MFG; MFG → AG
Model S6	Phonological lexicon; information transmission from the phonological lexicon to the phonology-to-orthography conversion	MFG; MFG → SMG

low) and syllable frequency (high, low) were both treated as within-participant variables.

The picture sets significantly differed in word frequency, high vs. low; $t(58) = 9.42, p < .001$, and syllable frequency, high vs. low; $t(58) = 9.57$, $p < .001$, but not in any of the following psycholinguistic attributes: number of orthographic neighborhoods, number of strokes, name agreement, image familiarity, image agreement, image complexity, and also phonological regularity. Eight additional pictures were selected from the same database as practice stimuli.

Three tasks were designed in the original fMRI study to identify neural substrates associated with certain processing components of Chinese handwritten production (see He et al., 2022, for more details): A *writing* task required participants to write down picture names, a *speaking plus drawing* task asked participants to name pictures covertly while drawing circles, and a *watching plus drawing* task required participants to look at a 3 × 3 square grid (comparable to the black-and-white line drawings) while drawing circles. There were 60 trials for the writing task and the speaking plus drawing task, respectively, but 20 trials for the watching plus drawing task. We designed 20 trials for the watching plus drawing task to avoid a potential fatigue effect because of a long scanning session (also see Rapp & Dufor, 2011). In addition, 20 trials of a null event were also included in which participants looked at a fixation cross.

The 160 trials were presented in a blocked fashion where five trials per task formed a block, resulting in 32 blocks in total. The order of blocks was counterbalanced across participants. Each participant had their own unique order of stimuli. Stimulus presentation was programmed using E-Prime 2.0 Software. Note that only the writing and watching plus drawing tasks were used for DCM analysis, as the present study aimed to identify optimal dynamic causal models associated with writing, without the involvement of the speaking plus drawing task.

Procedure

Participants went through three stages: familiarization, a behavioral test, and a test during the fMRI scanner. In the first two stages, participants were tested individually in a soundproof room where they sat at a comfortable viewing distance in front of the computer. During the familiarization stage, participants familiarized themselves with all pictures by viewing each picture for 3500 msec with the correct name printed below. Then, they were asked to write down the name of each picture within 5000 msec, followed by feedback on the correct name of the picture presented for 2000 msec. After this, participants were asked to correct their wrong responses by repeatedly writing the right names five times.

During the behavioral test, participants' writing responses and written onset latencies (i.e., the intervals from the onset of picture presentation to initial contact of the pen on the writing surface) were recorded by a WACOM Intuos A4 graphic tablet with a WACOM inking digitizer pen. Participants were asked to hover the stylus just above the corresponding line on the sheet of paper, which would avoid an arm movement when starting writing; they were asked to write their responses as quickly and accurately as possible without seeing their writing response. The behavioral test included eight practice trials (two trials per block) and 160 experimental trials (five trials per block, 32 blocks in total). In each block, a written instruction appeared on the screen to inform participants about the task they would be performing. Then, each of the pictures in a block was presented on the screen for 5000 msec subsequently (this period was long enough for finishing the writing of a picture name based on previous literature [e.g., Zhang & Wang, 2014]) during which participants made corresponding responses followed by a fixation cross with a variable intertrial interval of 2.5–7.5 sec. To avoid fatigue effects on writing performance, participants took a short break of 16 sec after completing the first 80 experimental trials. All participants performed at 97% writing accuracies, and it was assumed that the same performance would be executed during the fMRI scan because the fMRI test used the same experimental stimuli and program as the behavioral test (see also Segal & Petrides, 2012, for an identical procedure).

Finally, participants completed an fMRI test. Before entering the scanner, they received a short practice session of 10 min (with different picture stimuli from that in the scanning stage) to familiarize themselves with the requirements of the test and imitate what they would do in the scanner. They were instructed to hold a pencil gently and write their responses on the same spot on a piece of paper (i.e., one word was written on top of the other) as fast and accurately as possible (within 5 sec per trial) without seeing their responses, which would avoid hand and wrist movements as well as additional cognitive activities such as monitoring the spatial layout of the paper sheet. They went into the scanning stage only when they met the requirements, as judged by a trained experimenter. During the scanning stage, participants were provided a piece of paper resting on their right side next to their thighs and a pencil with which to make writing responses, and they were instructed to write picture names and draw circles in their normal writing style at the same location of the paper. Participants were also instructed to make corresponding responses following the instruction carefully, and their real-time performance would be monitored via a computer camera. The experimental program consists of eight practice trials (two trials per block) and 160 experimental trials (five trials per block), but with a different order of stimuli presentation.

fMRI Data Acquisition and Preprocessing

The functional images were recorded on a 3.0 T MRI scanner (GE Discovery MR750) using an EPI sequence with repetition time = 2000 msec, echo time = 30 msec, flip angle = 80°, field of view = 220 × 220 mm, matrix = 64 × 64. Each volume was composed of 36 slices covering the whole brain (slice thickness = 3 mm with 0.5-mm gap, voxel size = $3 \times 3 \times 3$ mm^3). To allow the magnetic resonance signal to reach equilibrium, a 6-sec dummy scan (i.e., 3 repetition time) was acquired at the beginning of the functional scan. The total scanning time was about 30 min. High resolution, T1-weighted anatomical images were obtained using a 3-D spoiled gradient-echo (SPGR) sequence with angle = 8°, field of view = 256 × 256 mm, matrix = 256 × 256, slice thickness = 1 mm. All fMRI data can be found at https://osf.io/t3kh7/.

Data preprocessing was performed with the software package SPM8 in MATLAB (Mathworks Inc.) including realignment, head motion correction, normalization, and spatial smoothing. The standard SPM analysis was performed by using the general linear model (GLM) approach (Friston et al., 1994). The GLM model for task contrast included onsets for the writing task and the watching plus drawing task. The GLM model for word frequency and syllable frequency consisted of onsets for four conditions generated by word frequency (high, low) and syllable frequency (high, low). For more details about the standard SPM analysis, see He and colleagues (2022). Anatomical localization of the group statistical maps was determined by using the Automated Anatomical Labeling toolbox (Tzourio-Mazoyer et al., 2002) and the SPM Anatomy Toolbox (Eickhoff et al., 2005).

DCM Analysis

DCM analysis first requires a hypothesis-driven definition of alternative network models that reflect different assumptions of how inter-regional interactions support a particular task. In other words, there are several competing DCMs representing different hypotheses. These models are then compared with each other based on the evidence from the present data by using a Bayesian model selection (BMS) procedure (Penny et al., 2010; Friston et al., 2003). The BMS procedure thus identifies the optimal DCM with the best trade-off between model fit and model generalizability (Penny, Stephan, Mechelli, & Friston, 2004).

Three sets of parameters are estimated by the BMS procedure (Penny et al., 2010; Friston et al., 2003): The parameter of *driving input* reflects the direct influences of experimentally designed inputs on specific brain regions, the parameter of *intrinsic connectivity* describes couplings among brain regions, and the parameter of *modulatory connectivity* shows how the intrinsic couplings are modulated by experimental variables. The posterior estimates of these parameters for the optimal model are further analyzed to enable inference on their magnitude and valence (positive or negative) at the group level, which reflects the rate of change (in Hz) of activity in one region that is associated with activity in another. Both DCM and BMS procedures were implemented by SPM12, which uses a far more robust optimization scheme than SPM8.

Selection of VOIs and Extraction of Regional Time Series

On the basis of brain activation identified at the group level in our standard SPM analysis (see He et al., 2022; now in Appendix B, Table B1) and previous literature, we selected five brain regions in the left hemisphere as VOIs for DCMs underlying Chinese handwritten production. All five VOIs were selected in the same contrast of writing > watching plus drawing. This is because this contrast revealed brain activation associated with the retrieval of orthographic information from the semantic activation of a pictured object (i.e., the central processes in Figure 1), and the five VOIs associated with the central processes identified in previous literature were activated in this contrast.

Specifically, in terms of the orthographic processes, we selected the left AG (BA 39; Montreal Neurological Institute [MNI] coordinate = [−27, −60, 39]) with significant activation as the VOI for the orthographic lexicon. This is also supported by the evidence that the left AG is associated with the storage of orthographic knowledge in the lexicon (e.g., Segal & Petrides, 2012, 2013; Carreiras et al., 2009; Booth et al., 2004; Joubert et al., 2004; Roeltgen & Heilman, 1984; Beauvois & Dérouesné, 1981). Note that we did not identify any activation in the left posterior inferior temporal gyrus/mid-fusiform gyrus (BA 37) that is widely regarded to be responsible for the processing at the orthographic lexicon level in writing (e.g., Beeson et al., 2003; Soma et al., 1989; Kawahata et al., 1988). This could be because this region is a part of the occipitotemporal stream that is specific for the visual word form processing (previously identified as the visual word form area; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002; Cohen et al., 2000), but the written picture naming task used in the present study may require less visual form processing than other writing tasks (e.g., orthographic form judgment in Chen et al., 2016; coping Chinese characters in Yang et al., 2019). We selected the left SFG (MNI mean coordinates [−18, −9, 69]) as the VOI for the orthographic buffer. This is consistent with previous evidence showing that the left SFG is specifically associated with the graphemic/orthographic buffer in writing (e.g., Rapp & Dufor, 2011; Cloutman et al., 2009).

Regarding the phonological processes, we regarded the left MFG (MNI coordinate = [−54, 0, 45]) with significant activation as the VOI for the phonological lexicon. This is because the left MFG activated in the present study is close to the phonological processing area (i.e., Rolandic sulcus; MNI coordinate = [−47, −6, 44]) identified in the meta-analysis study for language–brain relationships (Vigneau et al., 2006) at a distance of 9 mm. The left MFG has also been found to be associated with phonological processing in Chinese (Tan et al., 2005, 2003). We selected the left SMG (BA 40; MNI coordinate = [−36, −36, 57]) as the VOI for the phonology-to-orthography conversion. This is because the left SMG has been widely considered to be related to the sublexical processing of phonology-to-grapheme conversion involved in writing (e.g., Turkeltaub & Coslett, 2010; Sugihara et al., 2006).

In terms of semantic processing, we selected the left IFG (MNI coordinate = [−42, 6, 30]) with significant activation as the VOI. This is because this region is very close to (at a Euclidean distance of 6 mm) the semantic processing area (i.e., the left precentral gyrus/F3op junction, MNI coordinate = [−42, 4, 36]) identified in the meta-analysis study for language–brain relationships (Vigneau et al., 2006). The left IFG is also repeatedly identified for semantic processing (e.g., Heim, Eickhoff, & Amunts, 2009; Badre et al., 2005; Miceli et al., 2002).

For each VOI of each participant, the individual local maximum ($p < .05$ uncorrected; see also Mechelli et al., 2005) was identified that was closest to the group maximum within a spherical search volume of 16-mm radius. This approach ensured the comparability of extracted time series across participants by combining functional and anatomical constraints, despite the variation in individual activation patterns. As mentioned earlier, 14 out of the 21 participants had activations that met this criterion in all five VOIs and were considered for further analysis.

The time series of each VOI was extracted as the first principal component of all voxel time series within a

6-mm spherical radius centered on the individual local maximum. The average MNI coordinates [*x*, *y*, *z*] for the extraction of time series were the IFG = [−38.4, 5.1, 32.4], MFG = [−55.1, 0.2, 43.9], AG = [−27, −59.8, 39], SMG = [−36, −38.4, 54], and SFG = [−19.9, −9.9, 65.1]. The MNI coordinates for each participant are reported in Table 2.

Analysis 1. Definition of the DCMs with Different Intrinsic Connections

Four dynamic causal models (see Figure 2) with the five left-hemispheric regions (i.e., VOIs) were designed to evaluate four alternative hypotheses reflecting the relationship between phonology and orthography in Chinese handwritten production. In all models, the left IFG was assumed as the most likely brain region to receive driving input for written word production (i.e., writing task). The driving input reflects that the writing task drives hemodynamic responses and exerts a direct influence on the left IFG that is associated with semantic processing.

We first designed a relatively full model (i.e., Model 1) representing the weak orthographic autonomy hypothesis (Miceli et al., 1997) combined with a bidirectional lexicon route between the two lexicons (links C and E in Figure 1; Damian et al., 2011). That is, in Model 1, the representations in the orthographic and phonological lexicons can be directly activated from the semantic system, and the two lexicons map onto each other via a bidirectional lexical route. This was modeled such that both the MFG and the AG received information from the IFG (i.e., IFG → MFG, IFG → AG), and they connected with each other bidirectionally (i.e., MFG ↔ AG).

We then tested models by reducing the connectivity between the phonology and orthography lexicons. That is, Model 2 features the weak orthographic autonomy hypothesis (Miceli et al., 1997) that the orthographic and phonological representations can be directly activated from the semantic system and map onto each other via a unidirectional lexical route (link C in Figure 1), showing that both the MFG and the AG receive information from the IFG (i.e., IFG → MFG, IFG → AG), and there is a forward connection from the MFG to the AG (i.e., MFG → AG). Alternatively, Model 3 represents the strong orthographic autonomy hypothesis (Miceli et al., 1997) that both phonological and orthographic representations are accessed from the semantic system, but phonology influences the retrieval of orthography only via the sublexical route of phonology-to-orthography conversion (i.e., link D in Figure 1). Hence, in Model 3, both the MFG and the

Table 2. MNI Coordinates at which fMRI Time Series for the DCM Analysis Were Extracted in the Left Hemisphere

	IFG			*MFG*			*AG*			*SMG*			*SFG*		
Participant	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
01	−42	15	33	−57	−6	48	−21	−66	48	−36	−36	45	−18	−15	63
02	−48	12	36	−57	0	51	−18	−57	36	−27	−39	63	−18	−12	60
03	−45	0	33	−48	−3	42	−30	−51	39	−42	−36	54	−24	−12	63
04	−42	12	39	−57	−9	48	−30	−54	39	−30	−36	48	−9	−9	66
05	−42	6	24	−60	9	39	−24	−72	36	−42	−42	54	−18	0	57
06	−42	0	27	−51	6	39	−33	−66	33	−42	−39	60	−27	−9	72
07	−42	6	39	−60	3	39	−27	−60	45	−39	−45	48	−21	−12	63
08	42	0	30	−48	3	51	−30	−60	42	−36	−36	54	−15	−9	75
09	−51	6	42	−57	−3	48	−21	−57	33	−27	−30	54	−30	−15	60
10	−42	6	36	−54	9	45	−30	−66	42	−39	−36	54	−21	−9	60
11	−42	9	24	−63	0	36	−27	−57	51	−42	−39	54	−18	−15	63
12	−51	0	21	−54	0	36	−39	−57	30	−30	−48	63	−12	−12	72
13	−42	3	36	−51	0	48	−21	−60	36	−30	−39	54	−18	−3	72
14	−48	−3	33	−54	−6	45	−27	−54	36	−42	−36	51	−30	−6	66
Mean	−38.4	5.1	32.4	−55.1	0.2	43.9	−27	−59.8	39	−36	−38.4	54	−19.9	−9.9	65.1
RFX mean	−42	6	30	−54	0	45	−27	−60	39	−36	−36	57	−18	−9	69

The coordinates refer to the individual local maximum of the contrast "*Writing* > *Watching plus drawing*," which was closest to the local maximum of the group random effects (RFX) analysis (bottom row) in a sphere with a radius of 16 mm around the group maximum. AG = angular gyrus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; SFG = superior frontal gyrus; SMG = supramarginal gyrus. All brain regions are located in the left hemisphere.

AG receive information from the IFG (i.e., IFG → MFG, IFG → AG), but there is no connection between the MFG and the AG.

Finally, in Model 4, we assessed the obligatory phonological mediation hypothesis (Luria, 1970; Geschwind, 1969) that the retrieval of orthographic representations entirely depends on the prior phonological codes, such that only the MFG receives information from the IFG (i.e., IFG → MFG), and then sends the activation to the AG (i.e., MFG → AG).

Note that, in theory, a fifth model is plausible in which the AG, but the MFG does not, receives information from the IFG (i.e., IFG → AG), and then sends the activation to the MFG (i.e., AG → MFG). This model reflects that phonological representations are accessed from the orthographic lexicon via a backward link (link E in Figure 1), rather than from the semantic system directly. However, given that there is no evidence showing that the phonological representations cannot be accessed from the semantic system directly, this alternative model is not meaningful and it, thus, was not further considered.

Analysis 2. Definition of the DCMs with Modulatory Effects

As mentioned earlier, DCM employs an explicit model of coupling that allows for inferences about how directed effective connectivity between brain regions is affected by experimental factors (Friston et al., 2003). Thus, after determining the optimal model reflecting the relationship between phonology and orthography in the writing of Chinese characters, we further investigated how the optimal model was affected by two psycholinguistic variables, namely, word frequency (high, low) and syllable frequency (high, low). We compared six competing models representing possible loci at which the word frequency (high vs. low) and syllable frequency (high vs. low) might affect, respectively (see Figure 3 for word frequency and Figure 4 for syllable frequency). Consistent with the models in Analysis 1, the left IFG was assumed as the region that received driving input from the writing task.

Analysis 2.1 DCMs representing modulations of word frequency. As shown in Figure 3, Model W1 is based on the assumption that the word frequency effect occurs at an early lexical-semantic level (e.g., Qu et al., 2016), such that high versus low word frequencies modulate activation in the IFG differentially. Model W2 represents the possibility that word frequency affects the processing in the orthographic lexicon (e.g., Chen et al., 2016; Rapp & Dufor, 2011; Goodman & Caramazza, 1986), such that activation in the AG is modulated by high versus low word frequencies differentially. The Model W3 and W4 were designed based on an exploratory assumption that word frequency may modulate the information transmission associated with the lexical-semantic access or orthographic lexicon. Specifically, Model W3 specifies that high versus low word frequencies differentially modulate the information transmission from the semantic system to the orthographic lexicon, that is, the IFG → AG intrinsic connection. Model W4 signifies that word frequency modulates the information flow from the orthographic lexicon to the orthographic buffer, that is, the intrinsic connection of AG → SFG.

In the other two models, we tested combined modulations of word frequency on certain processing components and information transmission. Model W5 features the possibility that word frequency modulates activation in the IFG (indexing the lexical-semantic level) and the IFG → AG intrinsic connection (indexing information flow from the semantic system to the orthographic lexicon). Model W6 represents that word frequency affects activation in the AG (indexing the orthographic lexicon) and the intrinsic connection of AG → SFG (indexing information transmission from the orthographic lexicon to the orthographic buffer).

Note that the present study did not consider DCMs representing modulations of word frequency on phonological routes. This is because previous research has found that word frequency did not interact with syllable frequency in a written picture naming task (Zhang & Wang, 2014), suggesting that word frequency does not affect phonological processing in the writing of Chinese characters. This finding is also consistent with the proposal that the word frequency effect in Chinese cannot be attributed to the retrieval of phonological word form, as word frequency is not based on phonological representations (Wang & Zhang, 2021).

Analysis 2.2 DCMs representing modulations of syllable frequency. As shown in Figure 4, Model S1 is based on the assumption that the syllable frequency effect occurs at the phonological lexicon level (see O'seaghdha et al., 2010; Laganaro, 2005; Stenneken, Hofmann, & Jacobs, 2005), such that high versus low-syllable frequencies modulate activation in the MFG differentially. Models S2, S3, and S4 feature the possibility that syllable frequency modulates information transmission associated with the phonological lexicon. In Model S2, syllable frequency affects the information flow from the semantic system to the phonological lexicon, that is, the IFG → MFG intrinsic connection. The Model S3 and S4 were designed to test an exploratory assumption that syllable frequency may modulate the information transmission linking to the phonological lexicon. Specifically, in Model S3, high versus low-syllable frequencies modulate the information transmission from the phonological lexicon to the orthographic lexicon, that is, the MFG → AG intrinsic connection. In Model S4, syllable frequency impacts the information flow from the phonological lexicon to the phonology-to-orthography conversion, that is, the intrinsic connection of MFG → SMG.

In the other two models, a combination of mechanisms was implemented. That is, Model S5 specifies that syllable frequency modulates activation in the MFG (indexing the phonological lexicon) and the MFG → AG intrinsic connection (indexing information flow from the phonological lexicon to the orthographic lexicon). Model S6 signifies that syllable frequency modulates the MFG activation (indexing the phonological lexicon) and the intrinsic connection of MFG → SMG (indexing information transmission from the phonological lexicon to the phonology-to-orthography conversion).

DCM Model Selection and Parameter Test

To compare different models, we used a BMS procedure (Penny et al., 2004) that has been widely used in previous DCM studies on language processing (e.g., Heim, Eickhoff, & Amunts, 2009; Heim, Eickhoff, Ischebeck, et al., 2009). BMS is based on the so-called "model evidence," which is defined as the posterior probability $p(y|m)$ of the data y given a particular model m. Bayes factor (BF) was used to test how much evidence is in favor of one model (e.g., model i) relative to the other model (e.g., model j) provided by the experimental data, which was defined as the ratio of the model evidence for two models $p(y|m = i) / p(y|m = j)$. In such a pairwise comparison, a BF > 1 indicates evidence in favor of the first model (e.g., model i), a BF $= 1$ signifies equivalence of models, and a BF < 1 means evidence for the second model (e.g., model j).

However, the model evidence cannot be calculated directly, so instead, an approximation to the model evidence is used. Three model selection criteria have been proposed to approximate the log model evidence: Akaike's Information Criterion, the Bayesian Information Criterion, and the Free Energy (Stephan et al., 2010; Friston, Mattout, Trujillo-Barreto, Ashburner, & Penny, 2007; Penny et al., 2004). Because Free Energy has the relatively best model selection ability (i.e., better trade-off between model accuracy and complexity) and is then recommended by Penny (2012), we employed this criterion to approximate the log model evidence in the present study.

The model selection was conducted as follows. First, a model comparison was implemented using fixed effects (FFX) BMS in SPM12, and the DCM tool was used to compute exceedance and posterior probabilities (i.e., the likelihood of a model given the data) at the single-participant level. Second, BFs for the pairwise comparison of the competing models for each participant were calculated by using SPM12. Because individual participants represent independent observations, the group Bayes factor (GBF) for each pairwise comparison was then calculated as the geometric mean of all participant-specific BFs (also see Heim, Eickhoff, & Amunts, 2009; Smith, Stephan, Rugg, & Dolan, 2006).

After determining the best model, the posterior estimates of its model parameters (i.e., driving inputs, intrinsic connections, and modulations) from all participants were entered into one-sample t tests to test whether they were significantly different from zero by using SPSS 17. This approach of inference on model parameters is conceptually equivalent to a second-level analysis, which treats individual parameter estimates as random effects across participants (also see Heim, Eickhoff, & Amunts, 2009; Heim, Eickhoff, Ischebeck, et al., 2009). Note that the parameters would not remain significant under a Bonferroni correction for multiple comparisons (see also Osnes et al., 2011).

RESULTS

Table 2 displays the means of the coordinates of the maximally activated voxel for each participant and VOI, and the maximum coordinate from the group GLM random effects analysis. The means of the individual maximum coordinates are within 16 mm of the maximum coordinates given in the group analysis.

The Optimal Model Reflecting the Relationship between Phonology and Orthography

The pairwise comparison of the four models representing the different relationships between phonology and orthography revealed superior evidence in favor of Model 2 (see Figure 2). Specifically, Model 1 was inferior to Model 2 (GBF = 0.60). Model 2 received more evidence than Model 3 (GBF = 3.69E+08) and also outperformed Model 4 (GBF = 5.22). Moreover, there was positive evidence in favor of Model 1 relative to Model 3 (GBF = 2.23E+08) and Model 4 (GBF = 3.15). In addition, Model 3 was inferior to Model 4 (GBF = 1.42E−08). The individual BFs for each pairwise model comparison are presented in Table 3.

The random effects analysis (i.e., one-sample t tests) on the parameters of Model 2 receiving the highest evidence in the BMS procedure yielded the following results (see Table 4 and Figure 2). The parameter for the driving input into the left IFG was significantly greater than zero, mean = 0.03 Hz; $t(13) = 2.57$, $p = .023$, which suggests that activation in the left IFG is increased when the writing task is performed. The parameters for three intrinsic connections were significantly different from zero, including the IFG → MFG connection, $t(13) = 2.21$, $p = .046$; the IFG → AG connection, $t(13) = 2.44$, $p = .030$; and the MFG → SMG connection, $t(13) = 2.20$, $p = .046$. All of the intrinsic connection parameters were positive, suggesting that activation in one of the brain regions flows into its connected regions, thus increasing the activation level there. That is, the positive IFG → AG connection (mean = 0.38 Hz) indicates that writing-induced activation in the IFG results in an activation increase in the AG. Similarly, writing-induced activation in the IFG facilitates the activation in the MFG (mean = 0.27 Hz) and then adds to the activation in the SMG (mean = 0.25 Hz).

The parameter for the AG → SFG intrinsic connection was marginally significant, $t(13) = 2.13$, $p = .052$,

Table 3. Individual BFs, GBFs, and Standard Error of the Mean (*SEM*) for the Comparison of Models (Models 1–4) Reflecting the Relationship between Phonology and Orthography in Chinese Handwritten Production

Participant	*M1 vs. M2*	*M1 vs. M3*	*M1 vs. M4*	*M2 vs. M3*	*M2 vs. M4*	*M3 vs.M4*
1	**4.35E+06**	**1.66E+06**	**1.18E+07**	*3.81E−01*	**2.71E+00**	**7.10E+00**
2	*9.98E−01*	*9.98E−01*	**1.04E+00**	**1.00E+00**	**1.04E+00**	**1.04E+00**
3	*3.13E−09*	*1.66E−09*	*2.76E−10*	*5.31E−01*	*8.79E−02*	*1.66E−01*
4	**1.00E+00**	**1.00E+00**	**1.01E+00**	**1.00E+00**	**1.01E+00**	**1.00E+00**
5	*9.99E−01*	**1.00E+00**	**1.06E+00**	**1.00E+00**	**1.06E+00**	**1.06E+00**
6	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**
7	**1.00E+00**	**1.69E+121**	**1.00E+00**	**1.69E+121**	**1.00E+00**	*5.91E−122*
8	**1.00E+00**	**1.00E+00**	*9.97E−01*	**1.00E+00**	*9.97E−01*	*9.97E−01*
9	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**
10	**1.10E+01**	**4.82E+00**	**2.19E+09**	*4.38E−01*	**1.99E+08**	**4.54E+08**
11	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**
12	*5.72E−03*	*3.29E−03*	**1.10E+00**	*5.75E−01*	**1.93E+02**	**3.35E+02**
13	*9.85E−01*	*9.78E−01*	**1.08E+00**	*9.92E−01*	**1.10E+00**	**1.11E+00**
14	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**
GBF	*6.03E−01*	**2.23E+08**	**3.15E+00**	**3.69E+08**	**5.22E+00**	*1.42E−08*
SEM	3.11E+05	1.21E+120	1.56E+08	1.21E+120	1.42E+07	3.24E+07

The **bold** print represents comparisons that yielded positive evidence in favor of the first model (BF > 1), and the *italics* represent comparisons that gave positive evidence in favor of the second model (BF < 1). BF = Bayes factor; GBF = group Bayes factor; M = model.

implying that the activation in the AG is likely to increase the activation level in the SFG (mean = 0.40 Hz). There was a negative SMG → SFG intrinsic connection (mean = −0.21 Hz), but it did not reach a significant level, $t(13) = -1.68$, $p = .117$. In addition, the parameter for the MFG → AG intrinsic connection was positive but not significant, mean = 0.01 Hz; $t(13) = 0.18$, $p = .860$.

Table 4. Parameter Estimates of the Model with the Best Fit (Model 2) Reflecting the Relationship between Phonology and Orthography in Chinese Handwritten Production

	Mean (Hz)	*Standard Error*	*t*	*df*	*p*
Intrinsic connections					
Left IFG → left MFG	**0.27**	**0.12**	**2.21**	**13**	**0.046**
Left IFG → left AG	**0.38**	**0.15**	**2.44**	**13**	**0.030**
Left MFG → left AG	0.01	0.04	0.18	13	0.860
Left MFG → left SMG	**0.25**	**0.11**	**2.20**	**13**	**0.046**
Left AG → left SFG	*0.40*	*0.19*	*2.13*	*13*	*0.052*
Left SMG → left SFG	−0.21	0.13	−1.68	13	0.117
Driving input					
Left IFG: writing task	**0.03**	**0.01**	**2.57**	**13**	**0.023**

The **bold** print indicates significant parameters ($p < .05$), the *italic* print represents marginally significant parameters ($0.05 < p < .1$), and the regular print indicates nonsignificant parameters ($p > .1$). AG = angular gyrus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; SFG = superior frontal gyrus; SMG = supramarginal gyrus. All brain regions are located in the left hemisphere.

The Optimal Model Representing Modulation of Word Frequency

The pairwise comparison of the six models representing different modulations of word frequency revealed superior evidence in favor of Model W4, suggesting that the word frequency (high vs. low) modulates the intrinsic connection of AG → SFG. The individual BFs for each pairwise model comparison are presented in Table 5.

The random effects analysis (i.e., one-sample *t* tests) on the parameters of Model W4 receiving the highest evidence in the BMS procedure yielded the following results (see Table 7 and Figure 3). The parameter for the modulation on the AG → SFG connection by high word frequency, mean = 0.18 Hz, $t(13) = 1.86, p = .085$, was positive but only reached a marginally significant level, which indicates that there may be an increase in coupling strength of the AG → SFG connection when writing down picture names with high word frequency. In contrast, the intrinsic connection of the AG → SFG was not significantly modulated by low word frequency, mean = 0.001 Hz, $t(13) = 0.01, p = .996$. A schematic of the modulations of the model with the best evidence (i.e., Model W4) is shown in Figure 3.

The Optimal Model Representing Modulation of Syllable Frequency

The pairwise comparison of the six models representing different modulations of syllable frequency revealed superior evidence in favor of Model S2, indicating that the syllable frequency (high vs. low) modulates the intrinsic connection of the IFG → MFG. The individual BFs for each pairwise model comparison are presented in Table 6.

The random effects analysis (one-sample *t* tests) on the parameters of Model S2 receiving the highest evidence in the BMS procedure yielded the following results (Table 7 and Figure 4). The parameters for the modulation on the IFG → MFG connection by low-syllable frequency was significant, mean = −0.17 Hz, $t(13) = -2.52, p = .026$, suggesting that there is an inhibition in coupling strength of the IFG → MFG connection when writing down picture names with low-syllable frequency. However, the IFG → MFG intrinsic connection was not significantly modulated by high-syllable frequency, mean = −0.12 Hz, $t(13) = -0.92, p = .373$. A schematic of the modulations of the model with the best evidence (i.e., Model S2) is shown in Figure 4.

DISCUSSION

The present study employed DCM (Friston et al., 2003) to investigate the dynamics within a brain network for Chinese handwritten production consisting of the left IFG, the MFG, the AG, the SMG, and the SFG. We first investigated the neuronal mechanisms reflecting how phonological codes affect the retrieval of orthographic representations in Chinese handwritten production by comparing four alternative dynamic causal models. The BMS procedure (Penny et al., 2010; Friston et al., 2003) revealed that a model (i.e., Model 2 in Figure 2) featuring the intrinsic connections of IFG → MFG, IFG → AG, and MFG → AG received higher empirical evidence than other models. This finding indicates that orthographic representations can be accessed from the semantic system directly, and also can be accessed from the phonological lexicon via a forward lexical route, which is in line with the weak orthographic autonomy hypothesis (Miceli et al., 1997).

We further identified how the optimal dynamic network was modulated by word frequency (high vs. low) and syllable frequency (high vs. low) by comparing six competing models, respectively. The BMS procedure showed that a model (i.e., Model W4 in Figure 3) featuring that word frequency modulated the AG → SFG connection was superior to the other models, suggesting that word frequency affects the information flow from the orthographic lexicon to the orthographic buffer. A model (i.e., Model S2 in Figure 4) with the modulation of syllable frequency on the IFG → MFG connection received the best evidence relative to other models, indicating that syllable frequency influences the transmission of activated semantic information to the phonological lexicon. The present study, therefore, provides the first insights into how the neural regions interact with one another in a dynamic network to support Chinese handwritten production, and how this network is modulated by experimental variables, that is, word frequency and syllable frequency.

Relationship between Phonology and Orthography in Chinese Handwritten Production

The optimal dynamic causal model supporting Chinese handwritten production consists of six unidirectional intrinsic connections among five brain regions with the writing task as driving input on the left IFG (i.e., Model 2 in Figure 2). This model provides direct evidence for the weak orthographic autonomy hypothesis, which assumes that phonological and orthographic representations are directly accessed from the semantic system, and then map onto each other via a forward lexical route (Miceli et al., 1997). The parameter test revealed that the driving input of the writing task on the left IFG was significantly positive, which suggests that activation in the left IFG increases when performing the written word production task.

The parameters for all the six intrinsic connections were positive except the SMG → SFG connection, reflecting the enhancing flow of the information from one brain region to the other. Specifically, the IFG → AG connection is positive and significant, which suggests that an increase in the left IFG results in an increase of activation in the left AG region. Because previous literature shows that the left IFG is involved in semantic processing (e.g., Heim, Eickhoff, & Amunts, 2009; Badre et al., 2005; Miceli et al.,

Table 5. Individual BFs, GBFs, and Standard Error of the Mean (*SEM*) For the Comparison of Six Models (Models W1–W6) Representing Possible Modulations of Word Frequency

Participant	*M1 vs. M2*	*M1 vs. M3*	*M1 vs. M4*	*M1 vs. M5*	*M1 vs. M6*	*M2 vs. M3*	*M2 vs. M4*	*M2 vs. M5*	*M2 vs. M6*	*M3 vs. M4*	*M3 vs. M5*	*M3 vs. M6*	*M4 vs. M5*	*M4 vs. M6*	*M5 vs. M6*
1	**8.20E+06**	*7.85E−02*	*6.37E−02*	**1.20E+00**	**8.32E+06**	*9.57E−09*	*7.77E−09*	*1.46E−07*	**1.01E+00**	*8.12E−01*	**1.53E+01**	**1.06E+08**	**1.88E+01**	**1.31E+08**	**6.94E+06**
2	**6.06E+00**	*6.48E−02*	*6.44E−02*	**1.01E+00**	**6.10E+00**	*1.07E−02*	*1.06E−02*	*1.67E−01*	**1.01E+00**	*9.94E−01*	**1.56E+01**	**9.41E+01**	**1.57E+01**	**9.46E+01**	**6.04E+00**
3	**2.52E+06**	**1.02E+08**	**1.04E+08**	*7.77E−01*	**2.05E+01**	**4.06E+01**	**4.15E+01**	*3.08E−07*	*8.13E−06*	**1.02E+00**	*7.60E−09*	*2.01E−07*	*7.44E−09*	*1.96E−07*	**2.64E+01**
4	**5.10E+00**	*6.15E−02*	*6.13E−02*	**1.00E+00**	**5.11E+00**	*1.21E−02*	*1.20E−02*	*1.96E−01*	**1.00E+00**	*9.97E−01*	**1.63E+01**	**8.31E+01**	**1.63E+01**	**8.33E+01**	**5.11E+00**
5	**2.23E+00**	*2.70E−02*	*2.70E−02*	**1.00E+00**	**2.23E+00**	*1.21E−02*	*1.21E−02*	*4.50E−01*	**1.00E+00**	*9.98E−01*	**3.71E+01**	**8.26E+01**	**3.72E+01**	**8.28E+01**	**2.23E+00**
6	**6.24E+00**	*5.70E−02*	*5.69E−02*	**1.00E+00**	**6.24E+00**	*9.13E−03*	*9.12E−03*	*1.60E−01*	**1.00E+00**	*9.99E−01*	**1.76E+01**	**1.10E+02**	**1.76E+01**	**1.10E+02**	**6.24E+00**
7	**5.58E+00**	*6.38E−02*	*6.38E−02*	**1.00E+00**	**5.60E+00**	*1.14E−02*	*1.14E−02*	*1.79E−01*	**1.00E+00**	**1.00E+00**	**1.57E+01**	**8.77E+01**	**1.57E+01**	**8.77E+01**	**5.59E+00**
8	**6.26E+00**	*7.12E−02*	*7.10E−02*	**1.00E+00**	**6.27E+00**	*1.14E−02*	*1.13E−02*	*1.60E−01*	**1.00E+00**	*9.97E−01*	**1.41E+01**	**8.80E+01**	**1.41E+01**	**8.83E+01**	**6.25E+00**
9	**6.05E+00**	*7.54E−02*	*7.54E−02*	**1.00E+00**	**6.07E+00**	*1.25E−02*	*1.25E−02*	*1.65E−01*	**1.00E+00**	*9.99E−01*	**1.33E+01**	**8.05E+01**	**1.33E+01**	**8.05E+01**	**6.06E+00**
10	*7.13E−07*	*7.43E−02*	*3.74E−10*	**1.00E+00**	*6.94E−07*	**1.04E+05**	*5.25E−04*	**1.40E+06**	*9.72E−01*	*5.04E−09*	**1.35E+01**	*9.34E−06*	**2.67E+09**	**1.85E+03**	*6.94E−07*
11	**6.27E+00**	*5.79E−02*	*5.79E−02*	**1.00E+00**	**6.28E+00**	*9.23E−03*	*9.23E−03*	*1.59E−01*	**1.00E+00**	**1.00E+00**	**1.73E+01**	**1.08E+02**	**1.73E+01**	**1.08E+02**	**6.28E+00**
12	*1.23E−02*	*2.91E−04*	*2.72E−04*	**1.01E+00**	*1.27E−02*	*2.37E−02*	*2.22E−02*	**8.21E+01**	**1.03E+00**	*9.36E−01*	**3.46E+03**	**4.36E+01**	**3.70E+03**	**4.66E+01**	*1.26E−02*
13	**4.36E+00**	*5.65E−02*	*5.59E−02*	**1.02E+00**	**4.37E+00**	*1.30E−02*	*1.28E−02*	*2.33E−01*	**1.00E+00**	*9.90E−01*	**1.80E+01**	**7.73E+01**	**1.82E+01**	**7.81E+01**	**4.30E+00**
14	**6.13E+00**	*5.84E−02*	*5.84E−02*	**1.00E+00**	**6.14E+00**	*9.52E−03*	*9.52E−03*	*1.63E−01*	**1.00E+00**	**1.00E+00**	**1.71E+01**	**1.05E+02**	**1.71E+01**	**1.05E+02**	**6.14E+00**
GBF	**7.74E+00**	*1.88E−01*	*4.71E−02*	*9.98E−01*	**3.36E+00**	*2.43E−02*	*6.09E−03*	*1.29E−01*	*4.34E−01*	*2.50E−01*	**5.30E+00**	**1.79E+01**	**2.12E+01**	**7.13E+01**	**3.37E+00**
SEM	5.99E+05	7.30E+06	7.46E+06	2.23E−02	5.94E+05	7.43E+03	2.96E+00	1.00E+05	7.17E−02	7.14E−02	2.46E+02	7.57E+06	1.91E+08	9.33E+06	4.95E+05

M1–6 refers to Model W1–W6. The **bold** print represents comparisons that yielded positive evidence in favor of the first model (BF > 1), and the *italics* represent comparisons that gave positive evidence in favor of the second model (BF < 1).

Table 6. Individual BFs, GBFs, and Standard Error of the Mean (*SEM*) for the Comparison of Six Models (Models S1–S6) Representing Possible Modulations of Syllable Frequency

Participant	*M1 vs. M2*	*M1 vs. M3*	*M1 vs. M4*	*M1 vs. M5*	*M1 vs. M6*	*M2 vs. M3*	*M2 vs. M4*	*M2 vs. M5*	*M2 vs. M6*	*M3 vs. M4*	*M3 vs. M5*	*M3 vs. M6*	*M4 vs. M5*	*M4 vs. M6*	*M5 vs. M6*
1	**2.52E+06**	**1.02E+08**	**1.04E+08**	*7.77E−01*	**2.05E+01**	**4.06E+01**	**4.15E+01**	*3.08E−07*	*8.13E−06*	**1.02E+00**	*7.60E−09*	*2.01E−07*	*7.44E−09*	*1.96E−07*	**2.64E+01**
2	*4.30E−03*	*4.23E−03*	*4.23E−03*	**1.00E+00**	**1.00E+00**	*9.84E−01*	*9.84E−01*	**2.33E+02**	**2.32E+02**	**1.00E+00**	**2.36E+02**	**2.36E+02**	**2.36E+02**	**2.36E+02**	**1.00E+00**
3	*7.22E−11*	*2.43E−11*	*2.57E−11*	**1.00E+00**	**1.00E+00**	*3.37E−01*	*3.56E−01*	**1.39E+10**	**1.39E+10**	**1.06E+00**	**4.13E+10**	**4.12E+10**	**3.90E+10**	**3.90E+10**	*9.99E−01*
4	*9.03E−03*	*8.96E−03*	*8.96E−03*	**1.00E+00**	**1.01E+00**	*9.93E−01*	*9.93E−01*	**1.11E+02**	**1.12E+02**	**1.00E+00**	**1.12E+02**	**1.12E+02**	**1.12E+02**	**1.12E+02**	**1.00E+00**
5	*4.84E−03*	*4.79E−03*	*4.79E−03*	**1.00E+00**	**1.00E+00**	*9.90E−01*	*9.90E−01*	**2.07E+02**	**2.07E+02**	**1.00E+00**	**2.09E+02**	**2.09E+02**	**2.09E+02**	**2.09E+02**	**1.00E+00**
6	*8.93E−03*	*8.92E−03*	*8.92E−03*	**1.00E+00**	**1.00E+00**	*9.99E−01*	*9.99E−01*	**1.12E+02**	**1.12E+02**	**1.00E+00**	**1.12E+02**	**1.12E+02**	**1.12E+02**	**1.12E+02**	**1.00E+00**
7	*3.36E−03*	*3.36E−03*	*3.36E−03*	**1.00E+00**	**1.00E+00**	*9.99E−01*	*9.99E−01*	**2.98E+02**	**2.98E+02**	**1.00E+00**	**2.98E+02**	**2.98E+02**	**2.98E+02**	**2.98E+02**	**1.00E+00**
8	*1.10E−02*	*1.10E−02*	*1.10E−02*	**1.01E+00**	**1.01E+00**	**1.00E+00**	**1.00E+00**	**9.16E+01**	**9.15E+01**	**1.00E+00**	**9.15E+01**	**9.14E+01**	**9.15E+01**	**9.14E+01**	**1.00E+00**
9	*6.48E−03*	*6.46E−03*	*6.46E−03*	**1.00E+00**	**1.00E+00**	*9.96E−01*	*9.96E−01*	**1.55E+02**	**1.55E+02**	**1.00E+00**	**1.55E+02**	**1.55E+02**	**1.55E+02**	**1.55E+02**	**1.00E+00**
10	*1.01E−10*	*4.76E−11*	*4.60E−11*	**1.00E+00**	**1.01E+00**	*4.70E−01*	*4.54E−01*	**9.92E+09**	**9.92E+09**	*9.66E−01*	**2.11E+10**	**2.11E+10**	**2.19E+10**	**2.19E+10**	**1.00E+00**
11	*2.60E−03*	*2.60E−03*	*2.60E−03*	**1.00E+00**	**1.00E+00**	*9.99E−01*	*9.99E−01*	**3.85E+02**	**3.85E+02**	**1.00E+00**	**3.85E+02**	**3.85E+02**	**3.85E+02**	**3.85E+02**	**1.00E+00**
12	*5.83E−05*	*4.66E−05*	*4.65E−05*	**1.01E+00**	**1.01E+00**	*8.00E−01*	*7.97E−01*	**1.73E+04**	**1.73E+04**	*9.96E−01*	**2.16E+04**	**2.16E+04**	**2.17E+04**	**2.17E+04**	**1.00E+00**
13	**5.41E+01**	**5.33E+01**	**5.33E+01**	**1.22E+00**	**1.86E+00**	*9.86E−01*	*9.86E−01*	*2.25E−02*	*3.45E−02*	**1.00E+00**	*2.28E−02*	*3.50E−02*	*2.28E−02*	*3.50E−02*	**1.53E+00**
14	*7.72E−03*	*7.72E−03*	*7.72E−03*	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.30E+02**	**1.30E+02**	**1.00E+00**	**1.30E+02**	**1.30E+02**	**1.30E+02**	**1.30E+02**	**1.00E+00**
GBF	*2.54E−03*	*2.85E−03*	*2.85E−03*	*9.98E−01*	**1.30E+00**	**1.12E+00**	**1.12E+00**	**3.93E+02**	**5.12E+02**	1.00E+00	**3.51E+02**	**4.57E+02**	**3.50E+02**	**4.56E+02**	**1.30E+00**
SEM	1.80E+05	7.30E+06	7.46E+06	2.32E−02	1.39E+00	2.83E+00	2.90E+00	1.17E+09	1.17E+09	5.12E−03	3.21E+09	3.20E+09	3.09E+09	3.09E+09	1.81E+00

M1–6 refers to Model S1–S6. BF = Bayes factor, GBF = group Bayes factor. The **bold** print represents comparisons that yielded positive evidence in favor of the first model (BF > 1), and the *italics* represent comparisons that gave positive evidence in favor of the second model (BF < 1).

Table 7. Parameter Estimates of the Optimal Models Representing Modulations of Word Frequency (Model W4) and Syllable Frequency (Model S2)

Modulations	*Mean (Hz)*	*Standard error*	*t*	*df*	*p*
Word frequency (WF): Model W4 in Figure 3					
Left AG → left SFG by high WF	*0.18*	*0.10*	*1.86*	*13*	*0.085*
Left AG → left SFG by low WF	0.001	0.11	0.01	13	0.996
Syllable frequency (SF): Model S2 in Figure 4					
Left IFG → left MFG by high SF	−0.12	0.13	−0.92	13	0.373
Left IFG → left MFG by low SF	**−0.17**	**0.07**	**−2.52**	**13**	**0.026**

Bold print indicates significant parameters ($p < .05$), *italic* print indicates marginally significant parameters ($0.05 < p < .1$), and regular print represents nonsignificant parameters ($p > .1$). AG = angular gyrus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; SFG = superior frontal gyrus. All brain regions are located in the left hemisphere.

2002) and the left AG is associated with orthographic processing (Segal & Petrides, 2012, 2013; Joubert et al., 2004; Roeltgen & Heilman, 1984; Beauvois & Dérouesné, 1981), the positive connection of IFG → AG indicates that activated semantic information facilitates the retrieval of orthography in writing. This in turn implies that orthographic representation can be accessed from the semantic system directly, which does not support the obligatory phonological mediation hypothesis (Luria, 1970; Geschwind, 1969), which claims that the processing of orthographic representations entirely depends on prior retrieval of phonological codes.

We found that the intrinsic connections of IFG → MFG and MFG → AG were positive, but only the parameter for the IFG → MFG connection was significant. This finding suggests that activated semantic information in the left IFG significantly enhances the retrieval of phonological representations from the phonological lexicon in the left MFG, and these representations then flow into the orthographic lexicon located in the left AG. This provides evidence for the assumption that the phonological codes constrain orthographic access via a lexical route (link C in Figure 1; Bonin et al., 2001). However, one may argue that there may not be a lexical route between the phonological and orthographic lexicons because the MFG → AG connection did not reach a significant level (mean = 0.01 Hz, $p = .860$). This argument fails to receive evidence from our finding that the dynamic causal model without the lexical route (i.e., Model 3 in Figure 2) was inferior to the optimal model with the lexical route (i.e., Model 2 in Figure 2). If the lexical route does not exist, Model 3 should receive higher evidence than Model 2.

A plausible interpretation for the lack of significance of the MFG → AG connection is that the lexical route indeed exists, but it is not the dominant one for the transition from phonological codes to orthographic representations in Chinese handwritten production. The transition between phonology and orthography is mostly likely accomplished through a sublexical route of the phonology-to-orthography conversion (link D in Figure 1; Bonin et al., 2001). This interpretation receives some support from our finding that there was a cerebral pathway of the sublexical route in the optimal model, that is, the significant intrinsic connections of IFG → MFG → SMG, which suggests that activated semantic information significantly facilitates the retrieval of phonological representations in the phonological lexicon, and these representations considerably enhance the processing of phonology-to-orthography conversion. However, the absence of significance on the SMG → SFG connection (mean = −0.21 Hz, $t = -1.68$, $p = .117$) suggests that the sublexical route cannot be fully approved. The negative, but not significant, SMG → SFG connection implies that activated representations via the phonology-to-orthography conversion may not affect (or may even suppress) their temporary storage in the orthographic buffer.

Given that the lexical route (link C in Figure 1) and sublexical route (link D in Figure 1) are not fully approved by the parameter test of the DCM analysis, one may assume that the retrieval of orthographic representations in Chinese handwritten word production relies mostly on the orthographic autonomy pathway, that is, the intrinsic connections of IFG → AG → SFG. This assumption is supported by our results that the IFG → AG connection was significantly greater than zero, and the AG → SFG connection was positive and had a strong trend towards a significant level, mean = 0.40 Hz, $t(13) = 2.13$, $p = .052$. The cerebral pathway reflecting the orthographic autonomy processing implies that orthographic representations are accessed from the semantic system directly and then flow into the orthographic buffer to wait for further motor plan and execution.

Moreover, the reliance on the orthographic autonomy pathway is consistent with the fact that orthography and phonology are largely dissociated in Chinese (see also Qu, Damian, Zhang, & Zhu, 2011), as there are a large number of homophones in Chinese sharing a single syllable (i.e., pronunciation/pinyin) but have their own orthographic forms (e.g., the syllable is /jia1/ and its orthographic forms could be 家, 加, 佳, 夹, 嘉), resulting in the relatively arbitrary phonology-to-orthography correspondence (Tan et al., 2000). Note that the marginal significance of the AG → SFG connection may be because of the relatively few participants in the present study; future research with a larger sample size is needed to substantiate the cerebral pathway of orthographic autonomy in Chinese handwritten production.

In addition, the optimal model does not have the backward connection from the left AG to the left MFG (i.e., the AG → MFG connection), which suggests that the orthographic representations do not send feedback activation to the phonological lexicon in Chinese handwritten production. This finding does not support the proposal by Damian and colleagues (2011) that there should also be a backward link from the orthographic lexicon to the phonological lexicon (link E in Figure 1). Combined, these results suggest that the retrieval of orthography can be accessed from the semantic system directly and also can be assembled via a unidirectional lexical route and a sublexical route of phonology-to-orthography conversion. However, the orthographic processes of Chinese handwritten word production are likely to rely on the orthographic autonomy pathway.

Note that individual differences may affect the group-level results of DCM. This is because the classic BMS approach (Penny et al., 2010; Friston et al., 2003) did not take into account the interparticipant variability in effective connectivity. Thus, we also conducted a supplementary Parametrical Empirical Bayes (PEB) analysis (Zeidman, Jafarian, Corbin, et al., 2019; Zeidman, Jafarian, Seghier, et al., 2019) at a group level (see Appendix C for more details) to assess commonalities and differences across participants in the DCMs subserving Chinese handwritten production. The PEB approach showed a consistent finding with the classic BMS procedure that Model 2 received the highest evidence (see Appendix C, Figure C1), which further supports the weak orthographic autonomy hypothesis (Miceli et al., 1997). Within this model, the intrinsic connection of IFG → AG received strong evidence (posterior probability > 0.9), suggesting that semantic activation significantly facilitates the retrieval of orthography in the orthographic lexicon, and thus supporting the view that orthographic representation can be accessed from the semantic system directly (Miceli et al., 1997; Rapp & Caramazza, 1997; Rapp et al., 1997). The absence of significance in other intrinsic connections may be because of big individual differences in a relatively small sample size (i.e., 14 participants).

The Modulations of Word Frequency and Syllable Frequency on the Optimal Dynamic Network

The BMS procedure revealed the superiority of the model (i.e., Model W4 in Figure 3) in which high versus low word frequencies modulated the AG → SFG connection differentially, which suggests that word frequency affects information transmission from the orthographic lexicon to the orthographic buffer in Chinese handwritten word production. The finding does not support the dominant view that word frequency affects a certain processing stage in writing such as orthographic lexicon (Rapp & Dufor, 2011; Goodman & Caramazza, 1986) and/or an early lexical-semantic level (Qu et al., 2016).

The inconsistency of our findings with the dominant view may be because of methodological limitations in previous research. That is, the techniques used in previous studies, such as RT (e.g., Alario et al., 2004; Jescheniak & Levelt, 1994; Wingfield, 1968; Oldfield & Wingfield, 1965), event-related potentials (e.g., Qu et al., 2016), or standard SPM analysis (e.g., Chen et al., 2016; Rapp & Dufor, 2011), could not assess how the information transmission between processing components of writing is affected by word frequency. However, the DCM approach used in the present study can address the methodological limitation by examining how a certain brain region (reflecting a certain processing component) and/or effective connections between brain regions (reflecting information transmission) are modulated by word frequency, which sheds light on the hotly debated loci at which word frequency effect occurs.

The parameter test showed that the modulation of high word frequency on the AG → SFG connection was marginally significant, M = 0.18, $t(13) = 1.86$, $p = .085$, whereas the modulatory parameter for low word frequency did not reach a significant level. This finding suggests that the AG → SFG connection is engaged only when writing picture names with high word frequency. Moreover, to link neural network to behavioral performance, we correlated DCM parameters with written latencies across participants and found a significantly positive correlation between the modulatory parameter of high word frequency and written latencies ($r = .56$, $p < .05$), suggesting that stronger modulation by high word frequency on the AG → SFG coupling is associated with better writing performance. These findings imply that writing different types of words requires different processing mechanisms: Writing high-word frequency words facilitates the information transmission from the orthographic lexicon to the orthographic buffer, but such facilitation does not occur for the writing of low-word frequency words. The facilitated transmission of orthographic representations may be the mechanism underlying the word frequency effect that high word frequency words are produced faster than low-syllable frequency (Alario et al., 2004; Jescheniak & Levelt, 1994).

It is worth noting that the supplementary PEB analysis revealed a different optimal dynamic causal model (i.e., Model W3 in Figure 3) in which high versus low word frequencies modulated the intrinsic connection of IFG → AG (see Appendix C, Figure C2, left), suggesting that word frequency may affect information transmission from the semantic system to the orthographic lexicon in writing.

Within this model, both modulations by high and low word frequencies on the IFG → AG connection were negative but did not receive strong evidence (posterior probabilities < 0.9), which implies there may be a decrease or suppression on the IFG → AG coupling during writing words with high and low word frequencies. The inconsistency of the modulation by word frequency between the classical BMS and PEB approaches could be because of big individual differences in relatively small sample size, too few trials (i.e., 30 trials) in each condition, or differences in statistical analysis methods. More DCM studies need to be carried out to clarify the exact loci of the word frequency effect in Chinese handwritten production.

In terms of syllable frequency, the BMS procedure revealed a model (i.e., Model S2 in Figure 4) featuring the modulation of high versus low-syllable frequencies on the IFG → MFG intrinsic connection received higher empirical evidence than other models, suggesting that syllable frequency modulates the information transmission from the semantic system to the phonological lexicon in Chinese handwritten production. This is not consistent with previous literature that shows that syllable frequency affects the later stage of language production, that is, phonetic encoding in alphabetic languages (e.g., Laganaro & Alario, 2006; Levelt et al., 1999; Levelt & Wheeldon, 1994). Our finding suggests that the syllable frequency effect occurs at relatively early processes of Chinese word production, that is, the interface between the semantic system and phonological lexicon. This is consistent with the proposal that syllabic representations (e.g., syllable frequency) in Chinese are retrieved from the mental lexicon in the initial stage of phonological encoding because a Chinese character's phonology is defined at the syllabic level (O'Seaghdha et al., 2010). However, it seems that syllable frequency does not affect a certain process, but the information transmission from the semantic system to the phonological lexicon. This may imply that there is interactive activation between the semantic system and phonological lexicon. That is, the to-be-named picture activates its semantic information, which flows to the phonological lexicon in which syllable representations are retrieved, and these phonological representations then flow back to the semantic system. This possibility is needed to be tested in future research by comparing Model 2 (in Figure 2) with a model in which there is a backward connection from the left MFG (the phonological lexicon) to the left IFG (the semantic system).

Crucially, the modulatory parameters for both high and low-syllable frequencies were negative, but only the parameter for low-syllable frequency reached a significant level. This suggests that the connection strength of the IFG → MFG is weakened for writing picture names with low, but not for high, syllable frequency. This finding implies that writing low-syllable frequency words inhibits the transmission of activated semantic information flowing into the phonological lexicon, but such an inhibition is not obtained for high-syllable frequency words. The inhibition mechanism may be the one underlying the syllable frequency effect that high-syllable frequency words are produced faster than low-syllable frequency words (Levelt et al., 1999; Levelt & Wheeldon, 1994). That is, high-syllable frequency is stored and can be retrieved from the mental syllabary directly. However, low-syllable frequency is constructed or encoded online each time they are needed (Laganaro & Alario, 2006) in which it activates multiple syllabic neighbors (i.e., homophones in Chinese). To select the target syllable, individuals need to eliminate the competing neighbors, which may be achieved by inhibiting the information transmission from activated semantics to phonological representations. Yet, this interpretation needs to be further tested.

Consistent with the classic BMS procedure, the PEB analysis showed that high versus low-syllable frequencies modulated the intrinsic connection of IFG → MFG (see Appendix C, Figure C2, right), suggesting that syllable frequency influences the transmission of activated semantic information to the phonological lexicon. The modulation parameters by high- and low-syllable frequencies on the IFG → MFG connection were negative, but did not receive strong evidence (posterior probabilities < 0.9), implying a decrease or suppression of the connection during writing words with high- and low-syllable frequencies. Compared with the BMS, the absence of significance in the modulation of low-syllable frequency in PEB results may be because we took into account the individual differences.

In summary, our results failed to provide evidence for the proposal that word frequency and syllable frequency affect a certain processing component, but showed that word frequency may modulate the information transmission from the orthographic lexicon to the orthographic buffer via a facilitation mechanism, and syllable frequency influences the transmission of activated semantic information to the phonological lexicon via an inhibition mechanism.

In addition, our findings not only provide insights into theories of written language production but also show some specificity to Chinese writing processing. First, the optimal dynamic causal model (M2 in Figure 2) suggests that the basic architecture of the working model in alphabetic languages is fit for Chinese. That is, the orthographic representations can be accessed via both a lexical route (link A in Figure 1) and a sublexical route (links B and D in Figure 1). However, there was no backward link (link E in Figure 1) from the orthographic lexicon to the phonological lexicon. This could be because orthography and phonology are largely dissociated in Chinese, and the representations' retrieval from the two lexicons is less interrelated with each other than that in alphabetic languages. Second, the superiority of Model 2 provides evidence for the weak orthographic autonomy hypothesis (Miceli et al., 1997), which indicates that orthographic representations can be accessed from the semantic system directly, and also can be accessed from the phonological lexicon via a forward lexical route. This suggests that phonological codes play a role in the retrieval of orthographic representations, even in a non-alphabetic language. However, written word production in Chinese may rely mostly on the orthographic autonomy pathway (IFG → MFG → AG in Model 2). This implies that phonology influences the retrieval of orthographic representations at different extents in Chinese and alphabetic languages. More research is needed to investigate the different roles of phonology in different writing systems.

Third, our results show that word frequency and syllable frequency influence information transmission between processes, rather than specific processes, of writing. This provides a new insight into the locus of the effects of word frequency and syllable frequency in writing. We found that word frequency influences the information flow from the orthographic lexicon to the orthographic buffer, and syllable affects the transmission of activated semantic information to the phonological lexicon. This indicates that word frequency (as an orthographic effect) affects the later stage of the orthographic autonomy pathway (IFG → MFG → AG in Model 2), but syllable frequency (as a phonological variable) influences the early stage of the phonological mediation pathway (IFG → MFG → SMG). Moreover, the influence of word frequency is achieved via a facilitation mechanism, such that high word frequency words facilitate the processing that activated orthographic representations flow into an orthographic buffer for temporary storage. However, syllable frequency affects the writing via an inhibition mechanism, such that low-syllable frequency words inhibit the transmission of activated semantic information flowing into the phonological lexicon. This finding implies that psycholinguistic variables influence writing processing via different mechanisms. More DCM research is needed to reveal the underlying mechanism supporting writing in different language scripts.

Outlook

To the best of our knowledge, the present study is the first attempt using the DCM approach to investigate the connectivity architecture of neural substrates involved in Chinese handwritten production. Our results revealed the relationship between phonology and orthography in Chinese handwritten production at a dynamic neural interaction level, and also identified the exact loci where the effects of word frequency and syllable frequency occur. This study goes beyond the previous observation of specified neural substrates for certain processes of writing (e.g., Yang et al., 2018; Chen et al., 2016), and of correlations of fMRI time courses of different brain regions supporting writing (i.e., functional connectivity; e.g., Yang et al., 2019), which indicates that the DCM approach can be fruitfully used to further explore cortical dynamics supporting written production.

Although the present study yielded meaningful results, there are still some limitations and open questions. First, the selection of the VOIs for processing components involved in writing does not seem perfect. This is because only little is known about brain regions specific to processing components in Chinese handwritten production, which means there is limited literature we can refer to. Thus, the selection of the VOIs included in the DCMs here mainly relied on the group-level contrasts and the regional findings from prior studies across languages (e.g., English, Japanese) and research fields (e.g., spoken production, reading). Moreover, the relatively small sample size may also constrain the identification of typical brain regions for certain cognitive processes. This is because writing requires a series of complicated processes, which may lead to large individual differences in brain activation across participants, resulting in a relatively high dropout (7 of 21) of participants who failed to have their activation maximum in the five VOIs in our DCM analysis. Thus, the association between a specific brain region and a certain processing component in the present study could not be guaranteed perfectly. For instance, the function of the left AG, which was selected as the VOI for the orthographic lexicon, is still controversial (see also Purcell et al., 2011). It is not only associated with orthographic processing (e.g., Segal & Petrides, 2012, 2013; Joubert et al., 2004; Roeltgen & Heilman, 1984; Beauvois & Dérouesné, 1981) we assumed in the present study, but also involved in conceptual/semantic processing (e.g., Seghier, Kherif, Josse, & Price, 2011; Binder, Desai, Graves, & Conant, 2009), sublexical phoneme-grapheme conversion processes (e.g., Sheldon, Malcolm, & Barton, 2008; Hillis et al., 2002), or the processing in orthographic buffer (e.g., Buchwald & Rapp, 2009). The ambiguity of the functional role of the left AG could be because of functional heterogeneity, such that different tasks could involve dissociable functional regions of this region. The left SMG region regarded as the VOI for phonology–orthography conversation could also be involved in the processing of phonological buffer (Yue, Martin, Hamilton, & Rose, 2019). Moreover, the left IFG selected as the VOI for semantic processing may be also related to the control of semantic information (Ralph, Jefferies, Patterson, & Rogers, 2017) or phonological processing in language processing (Klaus & Hartwigsen, 2019; Jobard et al., 2003). Hence, to make sure the accuracy of selecting VOIs for dynamic causal models in written language production research, more studies, with larger sample sizes and more tasks/contrasts, are needed to explore specified neural substrates of processing components in the writing of Chinese.

Second, as indicated already, we did not apply a Bonferroni correction for multiple comparisons at a group-level analysis because the parameters failed to reach significance under the correction. This might well be explained by the weak power resulting from the small sample size and/or high dropout rate of participants in the present study, that is, only the data of 14 out of 21 participants from the original GLM analysis were included in the DCM analysis. The absence of significance in parameters after the correction may also be because the repetition of picture stimuli (i.e., three repetitions, for the familiarization firstly, then for the behavioral test, and finally for the fMRI test) might elicit adaptation to the stimuli and then alleviate the brain activation associated with the dynamic causal model supporting writing. Thus, a larger sample size and less repetition of stimuli should be considered in future research that explores effective connectivity among cortical regions subserving writing.

Third, we did not examine how word frequency and syllable frequency modulate the optimal dynamic causal model interactively because of relatively few trials in each condition (i.e., 15 trials). This could be addressed in further work by including a larger trial number per condition. The interactive modulations on the optimal DCM should provide more insights into how the dynamic network subserving writing is affected by experimental factors. In addition, we treated word frequency and syllable frequency as binary variables; future studies should explore them as continuous variables to increase the power of the dynamic causal models supporting written language production.

Fourth, it should be noted that the optimal model we identified is the one better than the rest, but this may be not the absolute best dynamic causal model supporting Chinese written word production. This is because of the small model space (four for writing, six for word frequency and syllable frequency) and potential individual differences in the present study. Future DCM studies on written language production should consider larger model space and the influence of individual differences. Finally, assessing whether the current finding can be replicated in other writing tasks (e.g., writing-to-dictation, spelling) and other languages (e.g., French, English) is a fruitful direction for future research, which should advance our understanding of the particularity and universality of the organization of writing system in the brain.

Conclusion

DCM and BMS procedure were employed to test alternative hypotheses about the relationship between phonological and orthographic representations, as well as the exact loci of word frequency and syllable frequency effects in Chinese handwritten production. It was shown that orthographic representations can be accessed from the semantic system directly and also can be assembled from the phonological lexicon via a lexical route and a sublexical route. This finding thus provides evidence for the weak orthography autonomy hypothesis (Miceli et al., 1997) and fails to support the proposal that there is a backward link from the orthographic lexicon to the phonological lexicon (Damian et al., 2011). Moreover, DCM revealed that word frequency may affect the information flow from the orthographic lexicon to the orthographic buffer via a facilitation mechanism, and syllable frequency influences the information transmission from the semantic system to the phonological lexicon through an inhibition mechanism. Notably, these insights could not be obtained using the conventional SPM analysis (He et al., 2022), but instead required an analysis of effective connectivity. It would be a fruitful direction for future research to use the DCM approach to assess the hypotheses of written language production in greater detail and larger sample size.

APPENDIX A: STIMULI USED IN THE PRESENT STUDY

Table A1. Sixty Pictures Used in the Present Study

High Word Frequency	
High-syllable frequency	烟, 钟, 耳, 火, 鱼, 旗, 脚, 鸡, 房, 叶, 镜, 羊, 鞋, 星, 树
Low-syllable frequency	球, 床, 船, 桥, 佛, 炮, 狗, 枪, 腿, 兵, 桌, 浪, 轮, 窗, 虫
Low Word Frequency	
High-syllable frequency	斧, 弓, 盒, 桶, 梳, 笛, 梯, 豹, 虾, 鼠, 梨, 钳, 锯, 燕, 鲸
Low-syllable frequency	锚, 熊, 猫, 爪, 拐, 茄, 蛙, 锤, 琴, 巢, 耙, 鞍, 袜, 鹅, 龟

APPENDIX B: RESULTS OF STANDARD fMRI ANALYSIS FOR 21 PARTICIPANTS IN HE AND COLLEAGUES (2022)

Table B1. List of Anatomical Regions, Volumes, Maximal *z* Values, and Peak Coordinates for the Writing > Watching Plus Drawing Contrast

			MNI Coordinates			*TAL Coordinates*		
Anatomical Region (Estimated Brodmann Area)	*Volume (Voxels)*	*Zmax*	*x*	*y*	*z*	*x*	*y*	*z*
Writing > Watching Plus Drawing								
Frontal lobe								
L supplementary motor area (BA 6)	693	5.39	−6	0	63	−7	−7	60
L supplementary motor area (BA 6)		4.79	−6	6	51	−7	−1	50
L SFG (BA 6)		4.58	−18	−9	69	−19	−16	65
L precentral gyrus (BA 9)	113	3.98	−48	6	39	−46	1	39
L MFG (BA 6)		3.83	−54	0	45	−52	−5	43
L IFG (BA 44)		3.80	−42	6	30	−40	1	31
Parietal lobe								
L superior parietal lobule (BA 7)	124	4.15	−27	−60	54	−27	−62	47
L inferior parietal lobule (BA 7)		3.84	−27	−51	54	−27	−54	47
L AG (BA 39)		3.76	−27	−60	39	−27	−61	33
L SMG (BA 40)	33	3.61	−36	−36	57	−35	−40	51

APPENDIX C: METHODS AND RESULTS OF A SECOND-LEVEL PEB ANALYSIS

Methods

To assess commonalities and differences across participants (between-participants variability) in the effective connectivity domain at the group level, we conducted a PEB approach (Zeidman, Jafarian, Corbin, et al., 2019; Zeidman, Jafarian, Seghier, et al., 2019). The PEB is a hierarchical Bayesian model that employs both nonlinear (at the first level) and linear (at the second level) analyses, which takes into account the variability in individual connection strength (i.e., the uncertainty over parameters by their covariance matrix), reducing the weight of participants with noisy data (Zeidman, Jafarian, Seghier, et al., 2019).

The PEB analysis includes the following main steps: (1) A full DCM (with all connections of interest switched on) was specified for each participant at the first level. (2) The full DCM per participant was fitted to data, which provided estimates of the connectivity parameters (i.e., expected values and covariance). (3) The first-level estimates from 14 participants were collapsed to perform PEB second-level (between-participants) analysis, in which separate PEB analyses were carried out to avoid dilution of evidence effect (Zeidman, Jafarian, Seghier, et al., 2019), one for the A (intrinsic connectivity) and C (driving input) matrices, and another one for the B (modulation) matrix. Because we were interested only in group means, we did not model other between-participants effects. The parameters of the PEB models thus represent the group average of each

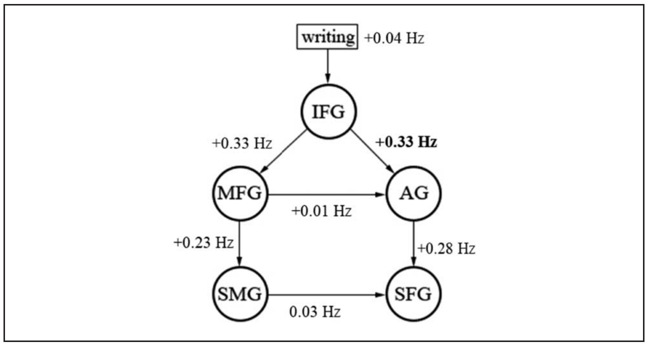

Figure C1. Significant parameter estimates (driving input and intrinsic connections) of the optimal model (Model 2 in Figure 2) reflecting the relationship between phonology and orthography in Chinese handwritten production. Numbers alongside regions or connections indicate their average parameter estimates. **Bold** print indicates values are significant at a posterior probability > 95%. AG = angular gyrus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; SFG = superior frontal gyrus; SMG = supramarginal gyrus. All brain regions are located in the left hemisphere. Writing refers to the writing task.

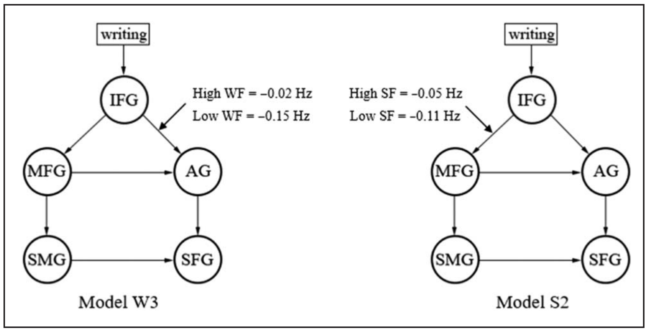

Figure C2. Significant parameter estimates of the optimal models representing modulations of word frequency (Model W3 in Figure 3, left) and syllable frequency (Model S2 in Figure 4, right). Numbers alongside the IFG → AG and IFG → MFG connections indicate their average parameter estimates. AG = angular gyrus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; SFG = superior frontal gyrus; SMG = supramarginal gyrus. All brain regions are located in the left hemisphere. Writing refers to the writing task.

connectivity parameter. (4) A Bayesian model reduction approach was conducted to search over the reduced PEB models with different combinations of connections (Friston et al., 2016; Friston & Penny, 2011). (5) Bayesian model average was performed to average the parameters across the best model from the Bayesian model reduction, weighted by the evidence of each model (Rosa, Friston, & Penny, 2012; Penny, Mattout, & Trujillo-Barreto, 2006).

Results

The Optimal Model Reflecting the Relationship between Phonology and Orthography

Similar to the classical BMS analysis, the PEB procedure showed higher evidence for Model 2 (model posterior probability = 0.39) than other models, in which the IFG sends activation to both the MFG and AG (i.e., IFG → MFG, IFG → AG), and the AG connects with the MFG via a forward link (i.e., MFG → AG). Note that the evidence was not strong in favor of the Model 2, that is, the model posterior probability was smaller than 0.9.

Within this model, we observed a significant increase in (excitatory) feedforward connectivity from the IFG to the AG (posterior probability > 0.99). See Figure C1 for a schematic of the optimal model representing the relationship between phonology and orthography in Chinese handwritten production.

The Optimal Model Representing Modulations of Word Frequency and Syllable Frequency

Inconsistent with the classical BMS analysis, the PEB procedure showed higher evidence for Model W3 (model posterior probability = 0.66) than other models, where high and low word frequencies modulated the intrinsic connection from the IFG to the AG. Note that the evidence is not strong in favor of the Model W2, that is, the model posterior probability is smaller than 0.9. Within this model, the IFG → AG connection was negatively modulated by high (−0.02 Hz; posterior probability = 0.74) and low (−0.15 Hz; posterior probability = 0.74) word frequencies, suggesting a decrease or suppression of the connection during writing words with high and low word frequencies. See Figure C2 (left) for a schematic of the optimal model reflecting modulation of word frequency.

Similar to the classical BMS analysis, the PEB procedure showed higher evidence for Model S2 (model posterior probability = 0.53) than other models, where high- and low-syllable frequencies modulated the intrinsic connection from the IFG to the MFG. Note that the evidence is not strong in favor of the Model S2, that is, the model posterior probability is smaller than 0.9. Within this model, the IFG → MFG connection was negatively modulated by high (−0.05 Hz, posterior probability = 0.74) versus low (−0.11 Hz, posterior probability = 0.74) syllable frequencies, suggesting a decrease or suppression of the connection during writing words with high- and low-syllable frequencies. See Figure C2 (right) for a schematic of the optimal model reflecting modulation of syllable frequency.

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Data Availability Statement

All stimuli, data, and related literature can be found on this article's project page on the Open Science Framework (https://osf.io/8wa2s/).

Author Contributions

Jieying He: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Validation; Visualization; Writing—Original draft; Writing—Review & editing. Qingfang Zhang: Conceptualization; Funding acquisition; Resources; Supervision; Writing—Original draft; Writing—Review & editing.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were M(an)/M = .407, W(oman)/M = .32, M/W = .115, and W/W = .159, the comparable proportions for the articles that these authorship teams cited were M/M = .549, W/M = .257, M/W = .109, and W/W = .085 (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this article report its proportions of citations by gender category to be: M/M = .55; W/M = .2; M/W = .183; W/W = .067.

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