

Neural substrates of Chinese lexical production: The role of domain-general cognitive functions

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ABSTRACT

Verbal fluency test, a type of word generation task, is a commonly used neuropsychological assessment. Among the healthy population, it has been used to assess verbal ability, but also executive functions. In the clinical field, verbal fluency has been used to support the diagnoses of a number of neuropsychological disorders. However, existing evidence do not allow for clear conclusions on whether such nonlinguistic uses of verbal fluency test are justified. The present study therefore investigated the involvement of domain-general cognitive functions in word production using functional magnetic resonance imaging, assessing verbal fluency, response inhibition, and working memory updating brain activations in the same set of participants. Results showed that response inhibition and working memory updating do play a role in verbal-fluency-type word production tasks, although language-specific regions are also required. Furthermore, domain-general and language-specific areas are closely neighboring subregions within the same broad brain regions. Additionally, a neural network for Chinese lexical production was observed, which corroborate neural bases for production in alphabetic languages, indicating that there is a core network for lexical production, regardless of language, production mode, or cue stimulus type, with other additional areas involved under some production conditions. Given that most previous research only investigated alphabetic languages, these results help gain a better understanding of language production mechanisms across languages.

1. Introduction

Verbal fluency test, a type of word generation task, is a commonly used neuropsychological assessment, first developed in the mid-20th century (see Benton, 1969). The test typically comprises two aspects, letter/phonemic fluency and category/semantic fluency, and requires participants to generate as many words as possible within a given timeframe that starts with a specified letter (letter fluency), or is an exemplar of a specified category (category fluency). The test is easy to administer, relatively brief, and has low resource demands. As such, it has been frequently used in scientific research and for clinical applications.

Among the healthy population, the test has been used to assess verbal ability, including word knowledge and lexical retrieval (e.g., Federmeier et al., 2010; Li et al., 2017; Shao et al., 2014; Weckerly et al., 2001).

Moreover, it is widely known as a paradigm for assessing executive functions (e.g., Fitzpatrick et al., 2013; Henry and Crawford, 2004; Herrmann et al., 2017; McDowd et al., 2011; Shao et al., 2014; Westwood and Romani, 2018). “Executive functions” is an umbrella term covering a range of multipurpose control mechanisms for regulating behavior. One widely accepted framework puts forward that executive functions comprise three component abilities, inhibition (inhibiting a dominant/prepotent response), shifting (shifting between task sets), and updating (updating and monitoring working memory representations; Miyake and Friedman, 2012; Miyake et al., 2000). Inhibitory control has further been divided into two aspects, interference suppression (suppressing irrelevant information present in the environment) and response inhibition (inhibiting inappropriate and prepotent response tendencies; Bunge et al., 2002). It is believed that the word retrieval process involved in verbal fluency engages non-language-specific

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processes, such as inhibition and updating (Costafreda et al., 2011; Henry and Crawford, 2004; Shao et al., 2014).

In the clinical field, verbal fluency has been used to support the diagnoses of a number of neuropsychological disorders, including Alzheimer's disease, amnesic mild cognitive impairment, schizophrenia, Parkinson's disease, attention deficit hyperactivity disorder, and bipolar disorder (e.g., Andreou and Trott, 2013; Costafreda et al., 2011; Ehli et al., 2007; Henry et al., 2004; Marchetta et al., 2008; Zhao et al., 2013). Apart from the readily accessible nature of the test, this is likely because impairments in language and executive functions are key features in many such disorders (e.g., Costafreda et al., 2011; Henry and Crawford, 2004; Tyburski et al., 2015). However, the performance of verbal fluency tests involves multifaceted psychological mechanisms, complicating the interpretation of its results (McDowd et al., 2011; Tyburski et al., 2015).

Conceptually, performance of verbal fluency tasks may engage response inhibition as well as working memory updating. Specifically, participants need to monitor and hold the retrieval criteria (e.g., no repetition, no morphological variants, no proper nouns or numbers) and continually update already produced items (Azuma, 2004; Rosen and Engle, 1997). They then also need to engage response inhibition to inhibit nonconforming (including repeated) items (McDowd et al., 2011; Piai et al., 2013), thus ensuring the appropriateness of continued output. Theoretically, models of spoken word production – such as the two-step model by Dell and colleagues (Dell et al., 2014; Dell & O'Seaghdha, 1992) and the lemma model by Levelt and colleagues (Indefrey, 2011; Indefrey and Levelt, 2004; Levelt et al., 1999) – postulate that during the lexical selection processes, semantically similar and semantically related words are simultaneously activated, resulting in competing responses. To overcome competition and generate the correct response, domain-general executive functions may be employed as a top-down regulatory mechanism to inhibit rival activations (Christoffels et al., 2007; Piai et al., 2013). Additionally, models have also described monitoring and control components during production, such as feedback control/perceptual loop and feedforward control systems (Guenther and Vladusich, 2012; Indefrey, 2011; Indefrey and Levelt, 2004; Nozari and Novick, 2017). Such systems may further entail domain-general processes to detect whether nonconforming responses are being produced, thereby ensuring speech planning and execution are in line with intent (Acheson et al., 2012; Piai et al., 2013).

The two aspects of verbal fluency – letter and category fluency – may engage executive functions in different ways, or to different extents. Category fluency bears closer resemblance to everyday language production, retrieving words through connections between concepts. Hence, category fluency more reflects verbal ability and the integrity of semantic memory. In contrast, letter fluency requires production from a phonemic category, and everyday speech production rarely engages such a process. Consequently, letter fluency performance requires novel retrieval strategies, and inhibition of responses that might normally be co-activated. When retrieving from a phonemic category, semantically similar or semantically related words that are co-activated mostly do not fit the criterion for production. When retrieving from a semantic category, on the other hand, semantically similar words often are suitable exemplars, and would thus facilitate generation of additional responses. Performing letter fluency tasks may, therefore, engage domain-general cognitive functions to a greater extent than performing category fluency (Azuma, 2004; Friesen et al., 2015; Henry and Crawford, 2004; Li et al., 2017; Shao et al., 2014; Thompson-Schill et al., 1997; Vigneau et al., 2006). Furthermore, neuroimaging research has shown that category fluency engages more frontotemporal language network regions for lexical-semantic lexical access, whereas letter fluency engages more prefrontal cognitive function regions for strategic retrieval (Baldo et al., 2006; Birn et al., 2010; Costafreda et al., 2006; Henry and Crawford, 2004; Li et al., 2017; Tupak et al., 2012; Whiteside et al., 2016).

In regard to the use of verbal fluency test for assessing cognitive

functioning and impairments other than verbal ability, existing evidence do not allow for clear conclusions on whether it is justified or not. Some findings support the notion that verbal fluency engages executive functions, for example a) verbal fluency performance was predicted not only by verbal ability but also by executive function ability (McDowd et al., 2011; Shao et al., 2014); b) compared to other measures of executive functions (e.g., Wisconsin Card Sorting Test), letter and category fluency have greater sensitivity and specificity for detecting frontal lobe dysfunctions (Henry and Crawford, 2004); and c) completion of verbal fluency tests entails neural features that are associated with executive functions, including both structural (e.g., higher grey matter density in basal ganglia) and functional features (e.g., activations in prefrontal cortex, supplementary motor area, and anterior cingulate; Birn et al., 2010; Grogan et al., 2009; Li et al., 2017; Libon et al., 2009). Other findings, however, indicate that verbal fluency only activates left hemisphere language regions, particularly areas associated with word form retrieval and covert articulation (Allen and Fong, 2008; Herrmann et al., 2017), or left hemisphere language-specific, rather than domain-general, cognitive control networks (Geranmayeh et al., 2014). Additionally, a factor analytic study found that category and letter fluency both only loaded onto a common language factor, and not onto an executive function factor (Whiteside et al., 2016).

The present study, therefore, primarily aimed to further investigate the involvement of domain-general executive functions in verbal fluency performance, focusing on letter fluency, response inhibition, and working memory updating. We assessed brain activations associated with each of these functions in the same group of participants. A second aim of this study was to investigate production processes in a non-alphabetic language (i.e., Chinese). Previous word generation research has mostly examined such processes in alphabetic languages (e.g., English). Although production processes generalize across languages to a certain extent (see e.g., Roelofs, 2015), alphabetic and non-alphabetic languages have fundamental differences in structure, and may thus have different processing mechanisms (Ge et al., 2015). During English word production, the first selectable phonological unit at the sublexical level (termed the "proximate unit") is the phoneme (O'Seaghdha, 2015). In contrast, the proximate unit in Chinese word production is the syllable (Chen and Chen, 2013; Roelofs, 2015). English production involves parallel activation of phonemic segments (i.e., content) and metrical frame in memory, followed by a serial association of content to frame. For Chinese production, the serial association is from stored atonal syllables to tonal frames (Roelofs, 2015). In Chinese, syllables are also complete characters, containing semantic information. Whereas the proximate unit in English, phoneme, is the smallest unit of sound, and although it can change the meaning of a word, it does not contain semantic information itself. Given these cross-language differences, Chinese and English production may differ in their cognitive and neural mechanisms.

Using functional magnetic resonance imaging (fMRI), we examined three modes of production: covert, overt, and handwritten; and two types of cue stimuli: letters (Chinese pinyin) and character radicals. Overt verbal fluency tasks have been used in behavioral and clinical neuropsychological assessments and in a small number of neuroimaging studies, while covert verbal fluency with letters is more widely used in fMRI studies, which minimizes artifacts caused by articulator movements. Regarding cue stimulus type, in addition to letters, the unique structure of the Chinese writing system provided a novel type of cue stimulus, nonexistent in alphabetic languages, namely radicals. Radicals are graphical components of Chinese characters, containing information relating to either pronunciation (phonetic radical) or meaning (semantic radical). Unlike production from letter (pinyin) cues, which involves phonological processing, lexical production from radical cues likely involves an orthographic processing pathway, using orthography-to-phonology transformations (Bi et al., 2009; Chen et al., 2002).

2. Method

2.1. Participants

Initially 23 right-handed volunteers from East China Normal University (ECNU) took part in the imaging experiment. Handedness was confirmed using the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were native Chinese speakers, had normal or corrected-to-normal vision, and no history of mental illness. One participant was excluded due to excessive head motion artifacts in the fMRI data (>10% outliers, see 2.6 for definition of outliers). Subsequent analyses thus included 22 participants (6 males; 22.4 ± 2.1 years, range 19–26 years).

Due to limited behavioral data and missing data issues in the imaging experiment, a replication behavioral experiment was conducted, with 44 new participants. One was excluded due to task performance at chance level, thus subsequent analyses included 43 participants (16 males; 21.6 ± 2.9 years, ranging from 18 to 30 years; all right-handed).

The study was approved by the Committee on Human Research Protection at ECNU. All participants gave written informed consent, and received financial reimbursement for participation.

2.2. Chinese verbal fluency tasks

There were two experimental and two baseline conditions, each comprising eight stimuli. For the pinyin experimental condition, phonologically distinct pinyin consonants were selected. Hebrew letters were used for the corresponding baseline, since they resembled pinyin letters visually, but were unlikely to be known and nameable by the present pool of participants. Radicals with highest frequency of appearance in unique Chinese characters were selected, ranging from 404 to 1035 characters according to the SUBTLEX-CH database (Cai and Brysbaert, 2010). Corresponding baseline stimuli were radical-like symbols, created by changing or moving strokes of existing radicals so that they did not resemble any actual radical (see Fig. 1).

Participants completed three runs of Chinese verbal fluency tasks in fMRI scanner, with the first involving covert production, the second overt, and the third handwritten. For the handwritten part, participants used pencil and paper placed next to their right hand, and were instructed to minimize movement (e.g., by writing in the same spot and not to be concerned with legibility). Each run consisted of 32 trials (4 types of stimuli \times 8 items per type), with each trial comprising two

events – first a fixation cross for 8 s, during which participants were instructed to rest, followed by a cue stimulus for 8 s, during which participants generated Chinese characters or performed the baseline task. For the covert and overt runs, the baseline was to continuously produce the sound “bou”, which is a nonexistent syllable in Chinese (i.e., does not have corresponding written form). For the handwritten run, the baseline was to repeatedly transcribe the symbol shown. The order of presentation of stimulus type was 1) pinyin experimental, 2) pinyin baseline, 3) radical experimental, and 4) radical baseline, fixed across the three runs. The presentation of individual stimuli within each type was in a pseudorandom order, optimized using Rorden’s fMRI Simulator (<http://www.mccauslandcenter.sc.edu/crnl/tools/fmristim>), and varied across runs.

For the imaging experiment, overt behavioral responses were recorded outside the scanner in a follow-up session. Using the traditional behavioral verbal fluency assessment procedure, participants ($n = 20$, 9.1% attrition) produced characters for three pinyin letters and three radicals (chosen from stimuli used in the scanning session), within 1 min time periods for each.

2.3. Executive function tasks

Stop-signal and n-back tasks were used to assess response inhibition and working memory updating respectively.

For the stop-signal task, letters “A” or “B” were presented (in uppercase), requiring participants to press either buttons “1” or “2” respectively. There were 160 trials in total, presented in an event-related design, with equal numbers of “A” and “B”. For 25% of trials (also with equal numbers of “A” and “B”), the letter initially presented in black text turned to red after a delay, indicating a “stop trial” where participants need to withhold responding. All stimuli appeared for 1000 ms in total. The stop-signal delay was initially 250 ms, and increased by 50 ms in the subsequent stop trial if participants successfully suppressed responding in the previous stop trial, and decreased by 50 ms if failed. Such an adaptive staircase procedure ensured an error rate of approximately 50%. Inter-stimulus interval (blank screen) was jittered, with 500 ms (35% of trials), 1000 ms (35%), 1500 ms (15%), and 2000 ms (15%) durations. A fixation cross for 500 ms was presented at the beginning indicating the start of the task. Trials were presented in a random order, as were inter-stimulus interval durations. A practice was performed outside the scanner prior to the experiment, consisting of 40 trials.

Two n-back tasks differing in the type of stimulus used were administered, each of which comprised a 2-back and a 0-back part. The first task comprised the eight phonologically distinct letters (presented in uppercase this time), and the second comprised the eight Hebrew letters (i.e., non-nameable symbols for the present pool of participants), used in the Chinese letter fluency task mentioned above (see Fig. 1). The use of non-nameable symbols was to minimize phonological processing of verbal stimuli. Together with a letter task, the two n-back tasks could allow a more holistic assessment of underlying working memory updating processes, independent of stimulus-specific properties. For 2-back, participants pressed “1” if the current stimulus was the same as the one presented two trials previously (i.e., targets; 25% of trials), and pressed “2” if different (i.e., foils). For 0-back, participants pressed “1” for the letter “X” or symbol “ ω ” of trials), and “2” for other letters or symbols. Each stimulus appeared for 500 ms, followed by a 2000 ms interval (black screen). There were 60 trials within each of the 2-back and 0-back parts, presented in a blocked design, with each block consisting of 12 trials (i.e., 5 blocks). There was a 10 s interval (fixation cross) between each block. A fixation cross for 500 ms was presented at the beginning indicating the start of the task. Target and foil trials were presented in a random order. Within each task, the 2-back part was performed first followed by 0-back. A separate block of 12 trials of the letter 2-back task served as practice outside the scanner.

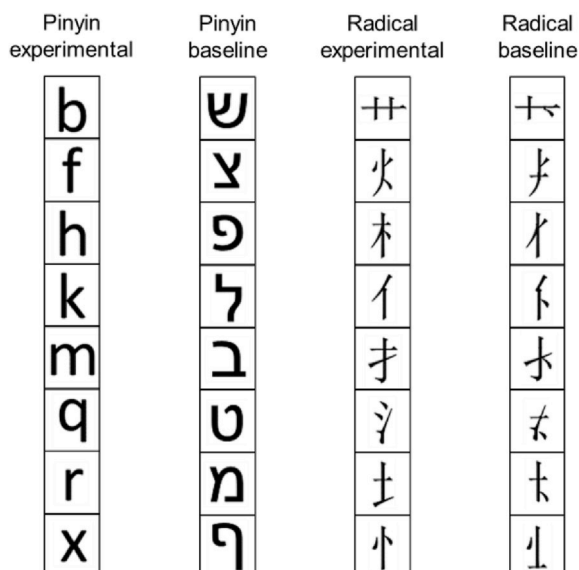


Fig. 1. Experimental and baseline cue stimuli for Chinese verbal fluency tasks.

2.4. General procedure

For the imaging experiment, an anatomical scan was first performed lasting approximately 6 min, followed by functional scans. The order of tasks was 1) covert production (9 min), 2) overt production (9 min), 3) handwritten production (9 min), 4) stop-signal task (6 min), 5) letter n-back task (6 min), and 6) symbol n-back task (6 min). Stimuli were presented using E-Prime 2.0 software. Key presses for the two executive function tasks were performed with a two-button keypad using participant's right hand, with the index finger for button "1" and middle finger for button "2".

For the replication behavioral experiment, two versions of overt verbal fluency (the 8 s version with eight stimuli per condition as performed in the scanner and the traditional 1 min version with three stimuli per condition), stop-signal, and the two n-back tasks were completed on a desktop PC, using the same stimuli and procedures as described above. Verbal responses were audio recorded and transcribed. Key presses were performed using the number pad on a standard keyboard.

2.5. Imaging data acquisition

MRI data were acquired using a 3T Siemens Trio scanner with an 8-channel head coil located at ECNU. High resolution T1-weighted anatomical images were collected using an MPR sequence: TR = 2530 ms, TE = 2.34 ms, FOV = 256 mm, FA = 7°, 1 mm slice thickness, 192 sagittal slices, 256 mm × 256 mm matrix. Functional data were obtained using an EPI sequence: TR = 2400 ms, TE = 30 ms, FOV = 192 mm, FA = 81°, voxel size = 3 × 3 × 3 mm³, 3 mm slice thickness, 40 interleaved slices, 64 mm × 64 mm matrix. At the onset of each run, task instructions appeared for 9.6 s (i.e., four volumes) to allow for T1 saturation effects. The first four scans of each run were excluded.

2.6. Imaging data preprocessing and analysis

MRI data analyses were performed using SPM8 (<http://www.fil.ion.ucl.ac.uk/spm/>) in MATLAB. Functional images for each subject were first corrected for slice-timing and head motion. Anatomical images for each subject were coregistered to a mean realigned EPI image, and segmented into white matter, grey matter, and cerebrospinal fluid. The anatomical image and all functional images were normalized to MNI space and smoothed with an 8 mm FWHM Gaussian kernel. To remove head movement artifacts, the ART toolbox (www.nitrc.org/projects/artifact_detect/) was used for each subject to produce a parameter file of head movement outliers, global mean z-threshold = 4 SD, movement threshold = 2 mm. The outlier parameter files were then modeled as regressors in individual-level analyses. Whole brain GLM analyses were conducted for each subject. At the group level, *t*-contrasts were carried out to examine task activations (experimental > baseline conditions).

3. Results

3.1. Behavioral results

Due to a technical error in the imaging experiment, n-back performance data was recorded for only 10 participants. Therefore, behavioral data analyses were conducted using data from the replication behavioral experiment (*n* = 43). Table 1 presents the mean scores for each task. Performance on the two versions of verbal fluency tasks (8 s blocks and 1 min blocks) were strongly correlated with each other for both pinyin and radical verbal fluency (*r*'s = 0.60, *p*'s < 0.001), thus only results from one version (8 s blocks, same as performed in the scanner) are reported.

Pearson correlations between tasks showed a significant negative correlation between stop-signal reaction time (SSRT) and total count for

Table 1

Behavioral task performance (mean ± standard deviation).

	Total count	
Chinese verbal fluency		
Pinyin cue	31.65 ± 6.09	
Radical cue	21.79 ± 4.77	
	Accuracy	Reaction time (ms)
Stop-signal task		
Stop trials	0.52 ± 0.04	261.14 ± 33.05 ^a
Go trials	0.98 ± 0.01	551.50 ± 100.58
Letter n-back task		
2-back	0.90 ± 0.09	768.15 ± 217.61
0-back	0.97 ± 0.02	496.69 ± 79.52
Symbol n-back task		
2-back	0.82 ± 0.09	773.41 ± 168.00
0-back	0.97 ± 0.03	512.02 ± 77.81

^a SSRT = latency of the stop process = nth percentile RT - mean stop-signal delay; *n* = number of go trials × proportion of failed stop trials; all go trials are included, with go omissions replaced by maximum RT (Verbruggen et al., 2019).

pinyin verbal fluency (*r* = −.32, *p* = .04), but not for radical verbal fluency (*r* = −0.09, *p* = .57; see Fig. 2A). For both n-back tasks, RTs were not significantly correlated with either pinyin or radical verbal fluency (smallest *p* = .20). Accuracy for the letter n-back task showed significant positive correlation with pinyin verbal fluency (*r* = −0.48, *p* = .001), but not with radical verbal fluency (*r* = −0.18, *p* = .25; see Fig. 2B). Accuracy for the symbol n-back task was significantly positively correlated with both pinyin (*r* = −0.37, *p* = .01) and radical verbal fluency (*r* = −0.33, *p* = .03; see Fig. 2C).

3.2. Imaging results

3.2.1. Chinese verbal fluency

Conjunction analyses, using conjunction null and native functions in SPM, were carried out to examine common activations across production modes, and two-way repeated-measures ANOVAs (factorial contrasts) were conducted to examine the effects of cue stimulus type and production mode. Fig. 3 and Table 2 present activation results for Chinese lexical production under different conditions.

For production from pinyin letter cues (pinyin cue > baseline), conjunction analysis showed common activations across the three production modes (covert, overt, and handwritten) in a widespread left hemisphere frontal-parietal-subcortical network, covering left inferior and middle frontal gyri (IFG, MFG), left precentral gyrus (preCG), left supplementary motor area (SMA), left inferior and superior parietal lobules (IPL, SPL), left angular gyrus (AG), left insula, left caudate, bilateral anterior cingulate cortex (ACC), and right cerebellum (Fig. 3A). For production from radical cues (radical cue > baseline), conjunction analysis showed activations across modes in mostly the same frontal and subcortical, but not parietal, regions as found for pinyin cues, namely left IFG, left MFG, left preCG, left SMA, left insula, left caudate, left thalamus, right ACC, and right cerebellum (Fig. 3B).

For handwritten production mode, both pinyin cue (pinyin cue > baseline) and radical cue (radical cue > baseline) production showed activations in frontal and subcortical regions, with production from pinyin (but not radical) cues also engaging parietal regions. Specifically, handwritten pinyin cue production activated left IFG, left superior frontal gyrus (SFG), left preCG, left SMA, left IPL, left SPL, left AG, bilateral insula, left caudate, right ACC, and right cerebellum (Fig. 3C top). Handwritten radical cue production activated bilateral IFG, left MFG, left SFG, left SMA, left insula, left ACC, and left caudate (Fig. 3D top). Activations for handwritten production without subtracting baseline (Fig. 3C and D bottom) showed greater involvement of sensorimotor-related areas, including more widespread activation of bilateral preCG, left SMA, and left postcentral gyrus (postCG).

For comparisons between pinyin cue and radical cue production, the

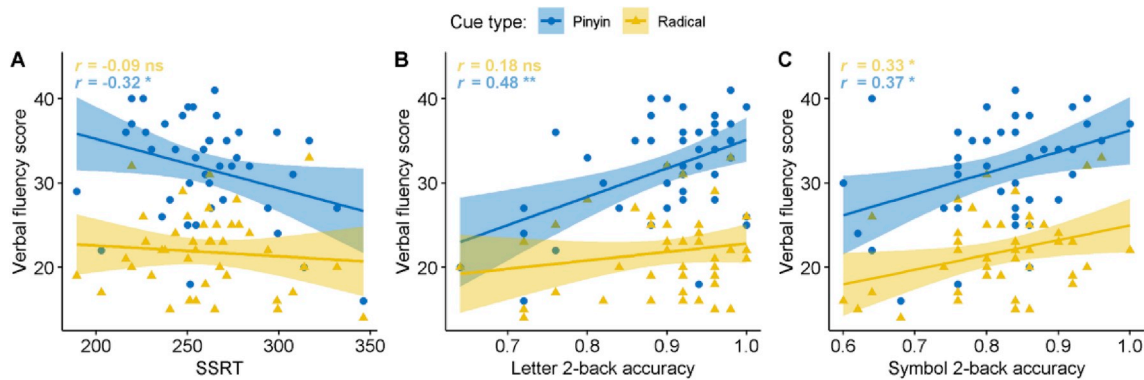


Fig. 2. Correlations between verbal fluency tasks and A) stop-signal task, B) letter n-back task, and C) symbol n-back task. Shaded areas indicate 95% confidence intervals. * = significant at $p < .05$. ** = significant at $p < .01$. ns = non-significant.

factorial contrast pinyin > radical showed activations in frontal, parietal, and subcortical regions, including left IFG, left MFG, left SMA, left preCG, left IPL, left SPL, left insula, and left putamen (Fig. 3E). The factorial contrast radical > pinyin, on the other hand, mainly involved bilateral occipital regions, including bilateral middle and right superior occipital gyri, and right lingual gyrus, along with left SFG and medial SFG, and left ACC (Fig. 3F).

For comparisons between covert and overt production, the factorial contrast covert > overt showed activations in bilateral anterior frontal and subcortical regions, including bilateral IFG and SFG, right insula, bilateral ACC, bilateral caudate, and left putamen (Fig. 3G). Whereas, the overt > covert factorial contrast activated bilateral posterior frontal and temporal regions, including bilateral preCG, left postCG, right SMA, bilateral superior temporal gyrus (STG), left hippocampus, and right parahippocampal gyrus (Fig. 3H).

To examine correlations between brain activity and behavioral performance, Spearman's rank correlation analyses were conducted with data from the imaging experiment participants who also completed out-of-scanner behavioral recording for verbal fluency tasks ($n = 20$; mean total count for pinyin verbal fluency: 48.30 ± 11.12 , mean total count for radical verbal fluency: 25.10 ± 8.08). Parameter estimate for a left IFG ROI (pars opercularis and pars triangularis) was not significantly correlated with either pinyin or radical verbal fluency performance (smallest $p = .66$). IFG Lateralization Index (LI) value (see 3.2.2 for LI analysis method and definition of symmetrical ROIs) showed a marginally significant positive correlation with pinyin verbal fluency performance ($\rho = 0.43$, $p = .058$; see Fig. 4A), and a positive trend for radical verbal fluency but was non-significant ($\rho = 0.34$, $p = .14$; see Fig. 4B).

3.2.2. Executive functions

For the stop-signal task, the contrast stop trials > go trials showed activations in widespread bilateral cortical and subcortical regions, covering bilateral IFG, bilateral MFG, right preCG, bilateral SMA, bilateral IPL, right SPL, bilateral AG, bilateral supramarginal gyrus (SMG), right precuneus, right inferior and bilateral middle temporal gyri (IGT, MGT), right STG, right temporal pole, bilateral inferior and middle occipital gyri, left fusiform gyrus, and left insula. For the n-back task, conjunction analysis (conjunction null) of the letter and symbol tasks (2-back > 0-back contrasts) showed activations in bilateral frontal and parietal regions, including bilateral IFG, bilateral MFG, left preCG, left SMA, bilateral IPL, bilateral SPL, bilateral precuneus, right middle occipital gyrus, left insula, and right putamen.

To examine the involvement of executive functions in verbal fluency, conjunction and disjunction analyses, using inclusive and exclusive masking respectively and native functions in SPM, were conducted to obtain common activations of verbal fluency with the different executive function tasks, and unique verbal fluency activations. Binary images

were first saved for response inhibition (stop-signal task stop trials > go trials) and working memory updating (2-back > 0-back, conjunction of the two n-back tasks). Image Calculator was then used to produce binary masks for the union of inhibition and updating, the intersection of inhibition and updating, inhibition exclusive of updating, and updating exclusive of inhibition. Conjunction or disjunction was performed as follows: verbal fluency (covert pinyin cue > baseline) exclusive of the union of inhibition and updating, verbal fluency inclusive of inhibition and exclusive of updating, verbal fluency inclusive of updating and exclusive of inhibition, and verbal fluency inclusive of the intersection of inhibition and updating.

Results showed that lexical production engaged both unique areas that are not associated with executive functions, as well as common areas overlapping with those functions (see Fig. 5A and Table 3). Unique verbal fluency areas mainly included frontal, parietal and subcortical regions in the left hemisphere, covering left IFG, left SFG, left preCG, bilateral SMA, left IPL, left SPL, left SMG, left middle occipital gyrus, left caudate, and right cerebellum. Common areas for verbal fluency, response inhibition, and working memory updating covered bilateral parietal regions, including bilateral IPL, left SPL, and right AG. Areas common to verbal fluency and inhibition exclusive of updating were mainly in the bilateral frontal and parietal areas, including left IFG, bilateral MFG, right SFG, bilateral SMA, bilateral IPL, left SPL, right AG, bilateral insula, and left putamen. Areas common to verbal fluency and updating exclusive of inhibition also involved bilateral frontal and left parietal areas, namely left IFG, left MFG, bilateral SFG, left preCG, bilateral SMA, left IPL, left SPL, and right ACC.

LI values for ROIs were computed via the LI toolbox (<http://www.medizin.uni-tuebingen.de/kinder/en/research/neuroimaging/software>) in SPM, using weighted mean LI and bootstrap methods (Wilke and Lidzba, 2007; Wilke and Schmithorst, 2006). Left and right IFG pars opercularis and pars triangularis were selected as anatomical ROIs, and symmetrized by overlapping original right and left regions with their flipped ones (Cai et al., 2013). The same was performed for left and right IPL and SPL. Verbal fluency activations showed the typical left-lateralized activation pattern (LIs > 0.5) for both frontal and parietal ROIs, whereas activations for response inhibition and working memory updating were not substantially lateralized (see Fig. 5B).

Percent signal change values for ROIs were computed using the MarsBar toolbox (<http://marsbar.sourceforge.net>) in SPM. Left and right frontal ROIs (spherical, radii = 6 mm) were selected based on verbal fluency activations, and included left and right IFG (centered at $-51, 14, 13$ and $54, 14, 16$ respectively) and left and right MFG ($-45, 20, 31$ and $45, 17, 28$). Verbal fluency showed significantly stronger activations in left IFG and MFG compared to right (p 's < 0.01). Response inhibition showed marginally stronger activations in right hemisphere ROIs compared to left (p 's < 0.10), though activations across all ROIs were relatively weak, possibly due to the relatively low number of trials

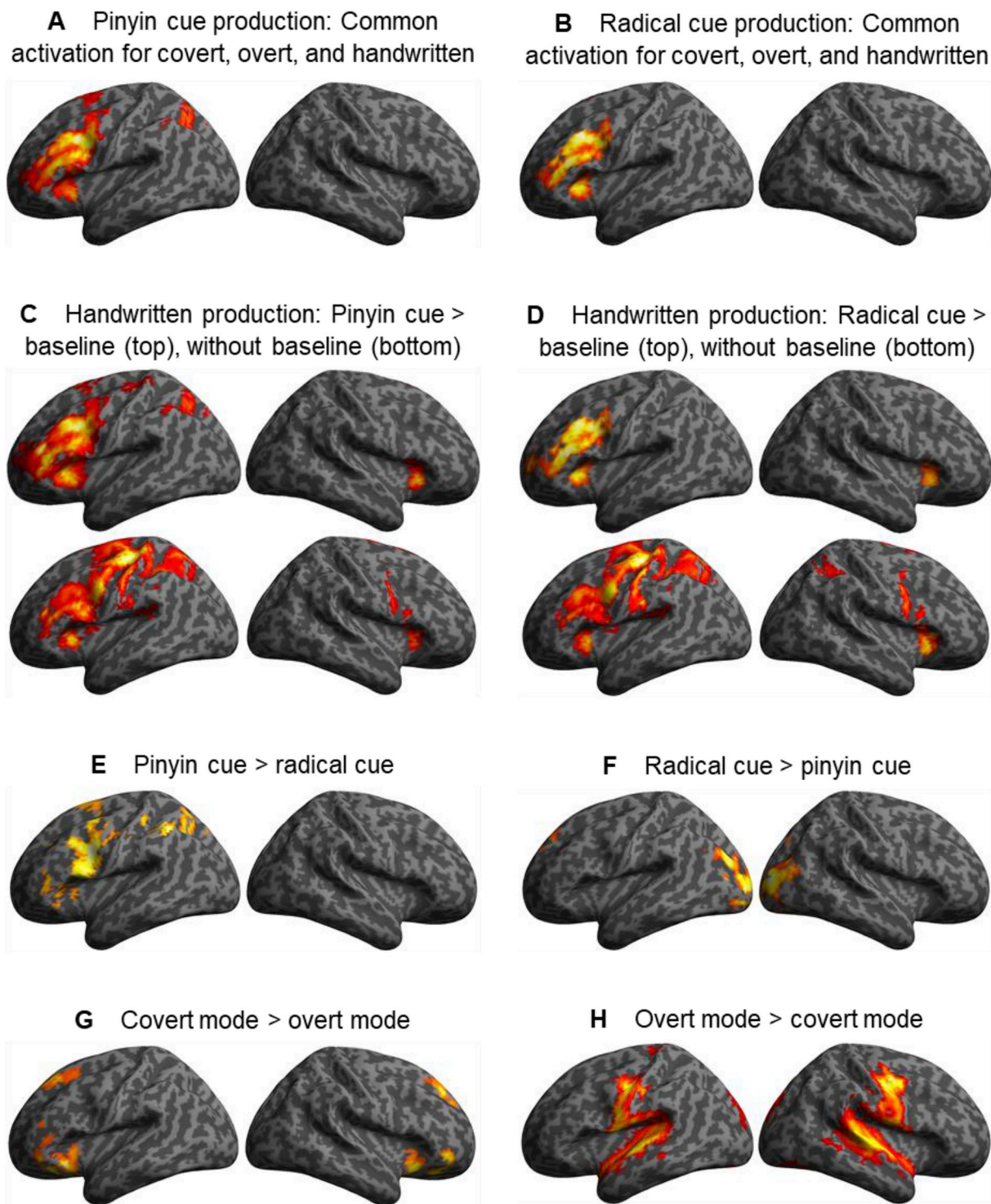


Fig. 3. Activations for Chinese verbal fluency under different conditions. Left and right hemispheres are shown on the left and right panels respectively. Voxel level $p < .005$ uncorrected, corrected by cluster level FDR $p < .05$.

in this event-related task, particularly the number of stop trials due to the nature of the task requirements (25%). For working memory updating, the letters task showed stronger activation in left MFG compared to right ($p < .01$), with no difference observed for left and right IFG ($p > .10$), and no differences between left and right ROIs for the symbols task (p 's > 0.10 ; see Fig. 5C).

3.2.3. Functional dissociation within left inferior frontal gyrus

The conjunction and disjunction analyses revealed that within left

IFG, the more ventral parts were unique to language production, whereas dorsal parts were involved for both working memory updating and language production (see Fig. 5A). To further investigate this functional dissociation, parameter estimates were extracted for dorsal and ventral IFG ROIs (cube, width = 10 mm) for each participant using MarsBar. The ROIs were selected based on a meta-analysis on verbal working memory showing a similar functional dissociation in left IFG (Chein et al., 2002). Original peak coordinates reported by Chein et al. (2002) were transformed into MNI space ($-46, 8, 27$ and $-43, 16, 5$)

Table 2
Activations for Chinese verbal fluency under different conditions.

Contrast	Cluster size	Area labels	MNI coordinates			t		
			x	y	z			
A. Pinyin cue production: common activation for covert, overt, and handwritten	2683	Left Inferior Frontal Gyrus	-42	8	28	9.85		
		Left Middle Frontal Gyrus	-30	47	7	4.56		
		Left Precentral Gyrus	-36	-1	61	4.85		
		Left Supplementary Motor Area	-6	17	49	8.39		
		Left Insula Lobe	-33	17	-2	6.08		
		Left Anterior Cingulate Cortex	-6	-1	28	4.53		
		Right Anterior Cingulate Cortex	12	26	37	4.86		
		Left Caudate Nucleus	-15	-1	19	6.16		
		285	Left Inferior Parietal Lobule	-39	-49	43	4.90	
			Left Superior Parietal Lobule	-30	-64	46	5.61	
			Left Angular Gyrus	-30	-52	37	5.34	
		B. Radical cue production: common activation for covert, overt, and handwritten	1121	Right Cerebellum	30	-61	-29	8.95
				Left Inferior Frontal Gyrus	-48	14	34	6.99
				Left Middle Frontal Gyrus	-33	53	10	3.85
				Left Precentral Gyrus	-45	11	31	6.76
Left Insula Lobe	-27			26	4	5.77		
485	Left Supplementary Motor Area			-6	14	49	6.19	
	Right Anterior Cingulate Cortex			12	29	28	3.71	
	Left Caudate Nucleus			-15	-4	22	4.35	
162	Left Thalamus			-12	-7	13	3.83	
	Right Cerebellum			33	-61	-29	5.05	
	Left Inferior Frontal Gyrus			-45	35	13	11.98	
C. Handwritten pinyin cue > baseline	5391			Left Superior Frontal Gyrus	-9	11	55	11.01
				Left Precentral Gyrus	-42	11	31	10.97
				Left Supplementary Motor Area	-3	20	46	11.29
				Left Insula Lobe	-30	29	7	9.05
		Right Anterior Cingulate Cortex	9	23	37	8.15		
		Left Caudate Nucleus	-15	-1	16	6.92		
		Right Cerebellum	30	-61	-29	9.72		
		402	Left Inferior Parietal Lobule	-39	-49	43	5.84	
			Left Superior Parietal Lobule	-30	-64	46	6.84	
			Left Angular Gyrus	-30	-52	37	5.84	
		222	Right Insula Lobe	36	17	1	8.44	
		153	Left Precentral Gyrus	-27	-28	61	4.14	
		D. Handwritten radical cue > baseline	1562	Left Inferior Frontal Gyrus	-42	26	13	7.02
				Left Middle Frontal Gyrus	-51	17	37	7.72
				Left Superior Frontal Gyrus	-21	53	4	5.30
Left Insula Lobe	-27			26	4	5.62		
Left Anterior Cingulate Cortex	-6			-1	28	3.30		
Left Caudate Nucleus	-15			2	22	5.57		
642	Left Inferior Parietal Lobule			-3	17	52	7.04	

Table 2 (continued)

Contrast	Cluster size	Area labels	MNI coordinates			t		
			x	y	z			
E. Pinyin cue > radical cue	1478	Left Supplementary Motor Area						
		Left Anterior Cingulate Cortex	-12	23	34	5.23		
		Right Inferior Frontal Gyrus	39	17	13	5.47		
		Left Inferior Frontal Gyrus	-51	11	11	4.52		
		Left Middle Frontal Gyrus	-33	2	50	4.40		
		Left Supplementary Motor Area	-6	5	65	4.93		
		Left Precentral Gyrus	-42	5	29	4.90		
		Left Insula	-30	20	5	3.31		
		Left Putamen	-18	8	2	4.57		
		465	Left Inferior Parietal Lobule	-42	-49	47	4.79	
			Left Superior Parietal Lobule	-30	-64	50	3.56	
			Left Superior Frontal Gyrus	-15	50	44	4.23	
		F. Radical cue > pinyin cue	545	Frontal Gyrus				
				Left Medial Superior Frontal Gyrus	0	62	17	3.93
				Left Middle Occipital Gyrus	-27	-91	5	5.50
Left Anterior Cingulate	0			35	8	3.80		
Right Middle Occipital Gyrus	30			-91	8	5.89		
Right Superior Occipital Gyrus	27			-82	38	3.59		
Right Lingual Gyrus	24			-88	-10	3.53		
443	Left Inferior Frontal Gyrus			-33	23	-13	5.66	
	Right Inferior Frontal Gyrus			27	26	-10	5.30	
	Left Superior Frontal Gyrus			-18	32	47	3.96	
G. Covert mode > overt mode	1740			Right Superior Frontal Gyrus	18	38	41	4.73
				Right Insula	36	20	-7	4.12
				Left Anterior Cingulate	-9	38	5	4.08
				Right Anterior Cingulate	12	38	23	4.51
				Left Putamen	-21	14	-7	4.07
		Left Caudate	-6	11	14	3.74		
		Right Caudate	9	14	11	4.44		
		10,433	Right Precentral Gyrus	42	-13	38	9.82	
			Left Postcentral Gyrus	-42	-16	35	8.90	
			Left Superior Temporal Gyrus	-60	-7	2	9.14	
		222	Right Superior Temporal Gyrus	63	-7	5	8.72	
		338	Left Hippocampus	-21	-7	-25	10.88	
			Right Parahippocampal Gyrus	24	-4	-25	10.82	
			Right Supplementary Motor Area	3	5	71	5.64	
		Left Precentral Gyrus	-6	-25	80	4.18		

Voxel level $p < .005$ uncorrected, corrected by cluster level FDR $p < .05$.

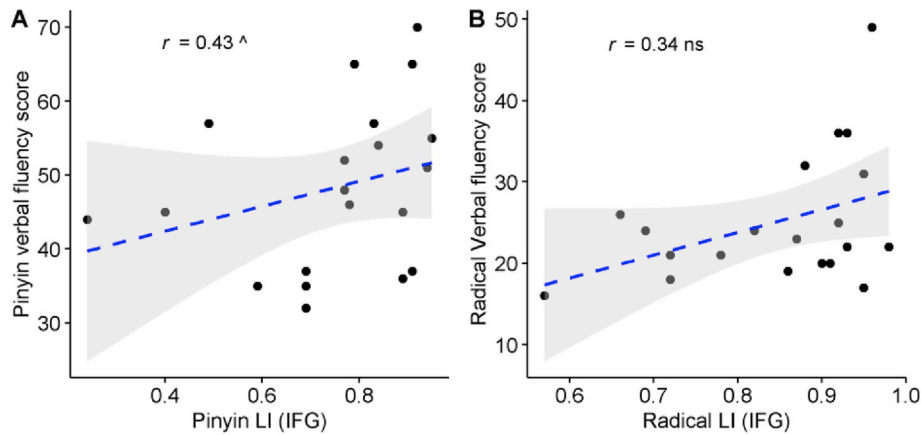


Fig. 4. Correlations between behavioral performance and Lateralization Index for A) pinyin verbal fluency and B) radical verbal fluency. Shaded areas indicate 95% confidence intervals. ^ = marginally significant at $p < .10$; ns = non-significant.

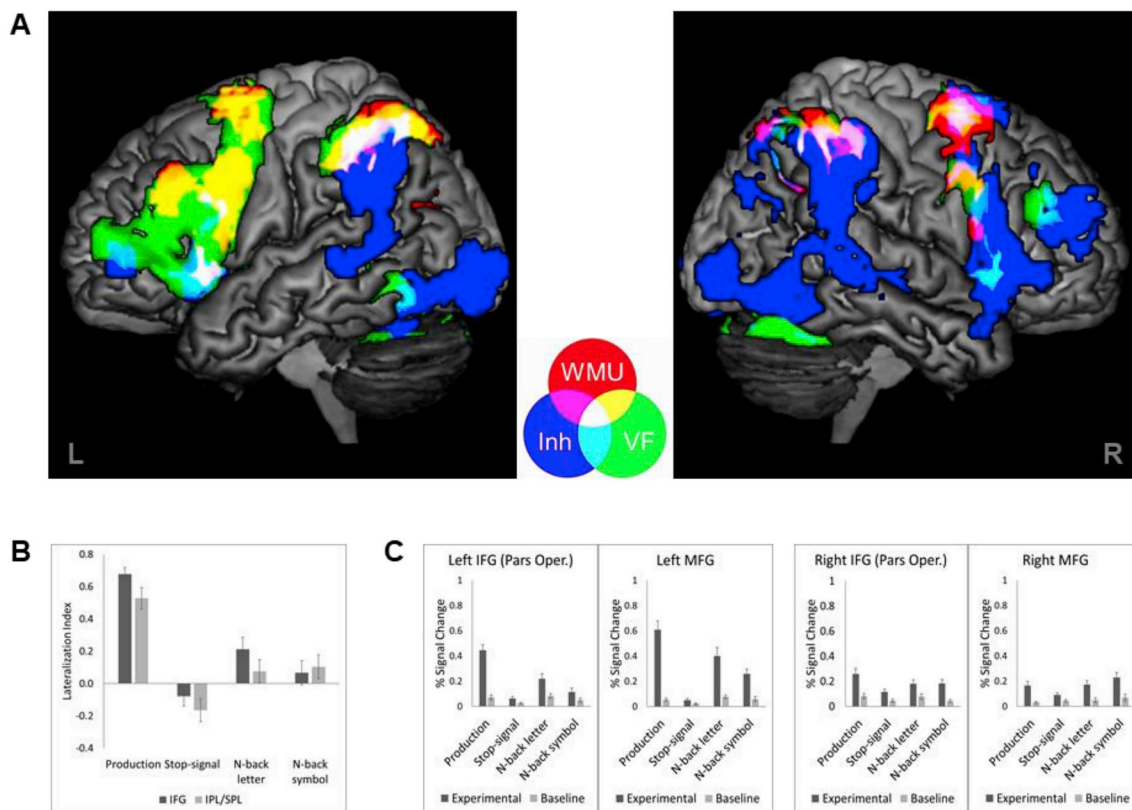


Fig. 5. A) Overlay of activations for Chinese verbal fluency (covert pinyin cue > baseline), response inhibition (stop trials > go trials), and working memory updating (2-back > 0-back, conjunction of the two n-back tasks). Green = verbal fluency unique. Blue = inhibition unique. Red = updating unique. Cyan = verbal fluency and inhibition overlap. Yellow = verbal fluency and updating overlap. Magenta = inhibition and updating overlap. White = verbal fluency, inhibition, and updating overlap. Images thresholded at cluster level FWE $p < .05$. Overlay of images created using MRICron (<https://www.nitrc.org/projects/mricron/>). B) Lateralization Index values for the four tasks (separately for letter and symbol n-back tasks) in IFG (pars opercularis and pars triangularis) and parietal (IPL and SPL) ROIs. C) Percent signal change values for the four tasks (separately for letter and symbol n-back tasks) in left and right IFG and left and right MFG ROIs. Error bars show standard errors of the mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and slightly adjusted so that the ROIs were covered within the IFG area (final ROIs were centered at $-46, 13, 24$ for dorsal and $-48, 16, 9$ for ventral; see Fig. 6A).

For verbal fluency tasks, one-sample t -tests showed that parameter estimates in both ROIs for both types of cue stimulus were significantly higher than zero (pinyin dorsal: $t = 10.00, p < .001$, Cohen's $d = 2.14$; pinyin ventral: $t = 6.85, p < .001$, Cohen's $d = 1.46$; radical dorsal: $t = 8.22, p < .001$, Cohen's $d = 1.75$; radical dorsal: $t = 4.00, p < .001$,

Cohen's $d = 0.85$; also significant after Bonferroni correction). Two-way repeated measures ANOVA showed significant main effects of type of cue stimulus ($F_{1,21} = 12.69, p = .002, \eta^2_G = 0.11$) and ROI ($F_{1,21} = 46.15, p < .001, \eta^2_G = 0.31$), and significant interaction between type of cue stimulus and ROI ($F_{1,21} = 7.35, p = .01, \eta^2_G = 0.01$). The dorsal ROI was more activated than ventral, and this effect was more obvious in pinyin than in radical cue production (see Fig. 6B).

For n-back tasks, one-sample t -tests (or Wilcoxon signed rank test for

Table 3
Conjunction or disjunction analysis results showing common and unique activations for verbal fluency and executive functions.

Analysis	Cluster size	Area labels	MNI coordinates			t	
			x	y	z		
Unique verbal fluency areas (covert pinyin cue > baseline)	6732	Left Inferior Frontal Gyrus	-42	11	22	9.35	
		Left Superior Frontal Gyrus	-21	-7	52	9.36	
		Left Precentral Gyrus	-48	5	19	9.21	
		Left Supplementary Motor Area	-3	8	67	8.83	
		Right Supplementary Motor Area	3	2	61	9.46	
		Left Caudate Nucleus	-15	-4	22	9.28	
		Right Cerebellum	24	-67	-26	11.06	
		254	Left Inferior Parietal Lobule	-51	-40	52	6.87
			Left Superior Parietal Lobule	-27	-73	55	5.68
			Left Supramarginal Gyrus	-42	-34	34	4.38
Left Middle Occipital Gyrus	-30		-70	40	4.00		
Areas common to verbal fluency and response inhibition exclusive of working memory updating	306	Right Middle Frontal Gyrus	33	5	61	5.12	
		Right Superior Frontal Gyrus	24	5	64	4.55	
		Left Supplementary Motor Area	-6	17	46	9.36	
		Right Supplementary Motor Area	3	11	55	12.33	
		417	Left Inferior Frontal Gyrus	-48	8	25	11.31
			Left Middle Frontal Gyrus	-33	44	1	4.91
			Left Insula Lobe	-27	14	7	6.22
		289	Left Putamen	-24	8	10	7.59
			Left Inferior Parietal Lobule	-30	-55	43	8.89
		315	Left Superior Parietal Lobule	-24	-67	52	6.95
Right Inferior Parietal Lobule	42		-43	52	5.86		
Right Angular Gyrus	30		-58	43	8.23		
234	Right Insula Lobe	36	20	1	6.57		
Areas common to verbal fluency and working memory updating exclusive of response inhibition	1056	Left Inferior Frontal Gyrus	-45	8	28	11.35	
		Left Middle Frontal Gyrus	-24	-4	49	9.81	
		Left Superior Frontal Gyrus	-24	-4	55	10.59	
		Right Superior Frontal Gyrus	30	5	61	5.60	
		Left Precentral Gyrus	-42	5	31	11.61	
		Left Supplementary Motor Area	-6	5	61	11.52	
		Right Supplementary Motor Area	3	8	55	12.94	
		Right Anterior Cingulate Cortex	9	23	40	6.42	
		475	Left Inferior Parietal Lobule	-36	-43	43	8.58
				-24	-70	55	7.05

Table 3 (continued)

Analysis	Cluster size	Area labels	MNI coordinates			t
			x	y	z	
Common areas for verbal fluency, response inhibition, and working memory updating	237	Left Superior Parietal Lobule				
		Left Inferior Parietal Lobule	-30	-55	43	8.89
	249	Left Superior Parietal Lobule	-24	-67	52	6.95
		Right Inferior Parietal Lobule	42	-43	52	5.86
		Right Angular Gyrus	30	-58	43	8.23

Voxel level $p < .005$ uncorrected, corrected by cluster level FWE $p < .05$.

non-normally distributed variable) showed that parameter estimates were significantly higher than zero only in the dorsal ROI (letter dorsal: $V = 217, p = .002$, effect size $r = 0.63$; letter ventral: $t = 1.27, p = .21$, Cohen's $d = 0.27$; symbol dorsal: $t = 3.42, p = .003$, Cohen's $d = 0.73$; symbol ventral: $t = 1.43, p = .17$, Cohen's $d = 0.31$). Two-way repeated measures ANOVA showed a significant main effect of ROI ($F_{1,21} = 9.35, p = .006, \eta^2_G = 0.06$), but not for type of stimulus ($F_{1,21} = 0.29, p = .59$). The interaction effect was also not significant ($F_{1,21} = 0.04, p = .85$). Like in the verbal fluency tasks, the dorsal ROI was again more activated than the ventral one (see Fig. 6C).

4. Discussion

Using behavioral measures and fMRI, the present study examined the involvement of domain-general executive functions in verbal-fluency-type lexical production tasks, as well as the neural bases of Chinese lexical production across different production modes and different cue stimuli.

4.1. Involvement of executive functions in verbal fluency

Behavioral results showed that performance on domain-general response inhibition and working memory updating tasks were related to pinyin (letter) verbal fluency task performance. The stronger the inhibition (lower SSRT) and updating (higher accuracy) abilities were, the better the verbal fluency performance. This relationship was less robust in radical verbal fluency, only showing a relationship with the symbols n-back task. Differences between pinyin cue and radical cue production (see detailed discussion in 4.2) may have resulted in domain-general executive functions being less involved in radical cue production. Thus, subsequent imaging data analyses on overlap between verbal fluency and executive functions mainly focused on pinyin verbal fluency.

Imaging results showed, firstly, that verbal-fluency-type word production tasks engaged both regions that are language-unique (exclusive of areas activated by domain-general executive function tasks) and those that are domain-general (overlap with areas activated by executive function tasks). Overlap with inhibition (exclusive of updating) mainly covered bilateral prefrontal, SMA, parietal, and insular areas. Overlap with updating (exclusive of inhibition) also included bilateral, though predominantly left, prefrontal areas, left motor cortex, bilateral SMA, left parietal lobe, and right ACC. Areas unique to verbal fluency involved left hemisphere cortical areas along with right cerebellum, mainly in prefrontal, motor, SMA, and parietal areas.

These results indicate that performance of verbal fluency tasks activates areas that are also activated when performing executive function tasks (assessed in the same participants), including the prefrontal cortex, SMA, and parietal areas. Moreover, it appears that both language-specific and domain-general regions are likely to be involved, in line with the notion that human cognition (including language) is underlay by the joint mechanisms of both specialized and general-purpose brain

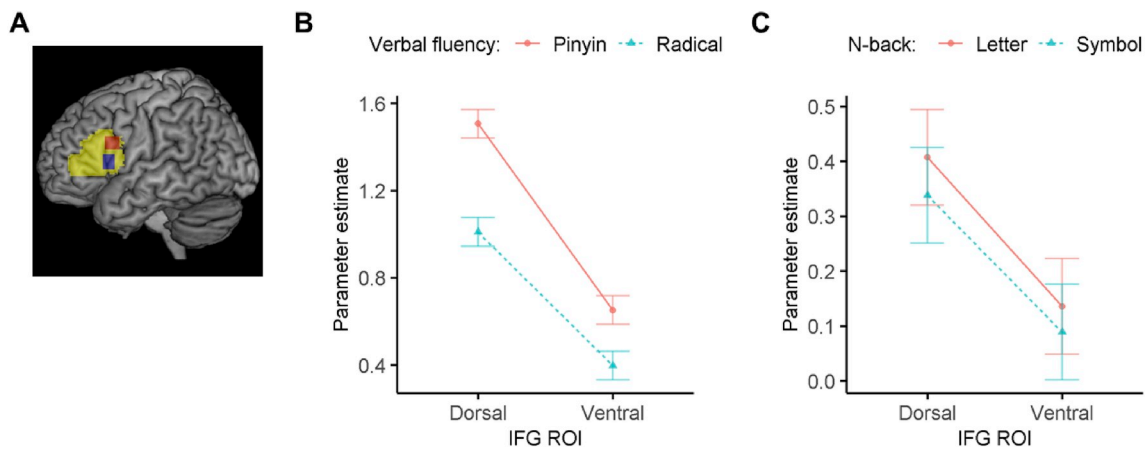


Fig. 6. A) Dorsal and ventral IFG ROIs (cube, width = 10 mm; centered at 46, 13, 24 for dorsal and -48, 16, 9 respectively); parameter estimates for B) verbal fluency tasks and C) working memory updating tasks. Error bars show standard errors of the mean.

regions (Fedorenko et al., 2013). It has been suggested that there exists a “multiple-demand” system, which, together with task-specific areas, allow us to perform a host of tasks requiring high-level cognition, such as mental arithmetic, manipulating information in working memory, and inhibiting task-irrelevant information (Duncan, 2010; Fedorenko et al., 2013). It remains unclear at present the precise manner in which domain-general functions are involved in domain-specific processes. Some possibilities open for future explorations are discussed below (see 4.3).

Secondly, our results showed that overlapping and unique areas are closely neighboring subregions within the same broad brain region. Specifically, there was a functional dissociation within left IFG, where the more dorsal area showed activations for both working memory updating and verbal fluency, whereas the ventral area only showed activation for verbal fluency. Although both dorsal and ventral IFG were involved in verbal fluency, the dorsal region was more strongly activated than ventral, particularly for pinyin verbal fluency. This interaction is consistent with the observation that pinyin verbal fluency performance is more strongly related to domain-general task performance, and suggests that the two areas have different functions in verbal fluency tasks. Together with the observation that only the dorsal region is significantly activated in working memory updating tasks, these results indicate that the ventral IFG region is language-specific and the dorsal domain-general.

Previous findings have also shown that language-specific and domain-general areas may not overlap, even though they may be close neighbors spatially (Basilakos et al., 2018; Chein et al., 2002; Fedorenko et al., 2012). In one study, Fedorenko et al. (2012) found two non-overlapping but adjacent set of subregions within Broca’s area (pars opercularis of left IFG), one that is language-specific (more central portions) and one that is domain-general (more surrounding portions). Other studies have differentiated two subregions within left IFG, where the dorsal subregion was shown to track performance of verbal working memory tasks, while the ventral portion showed sensitivity to lexicality (word or nonword status; Chein and Fiez, 2001; Chein et al., 2002). Our results support the differentiation of dorsal and ventral left IFG, with more ventral portions showing language-specific processing, and more dorsal portions showing common activations for language production and domain-general working memory updating.

Thirdly, the present results showed that bilateral parietal regions were the only regions common to verbal fluency, response inhibition, and working memory updating. The left parietal lobe also showed large areas of overlapping activation for verbal fluency and working memory updating. Only very small parts of the parietal lobe show production-unique activation. These results suggest that the role of the parietal lobe in language production may well be one of domain-general

cognitive processing. A meta-analytic study covering neuroimaging studies for nine different cognitive domains showed that different linguistic and non-linguistic tasks all activated parietal areas (Humphreys and Lambon Ralph, 2015). The parietal lobe was, therefore, suggested to hold a domain-general processing system (Humphreys and Lambon Ralph, 2015; 2017). The dorsal areas (IPL, SPL, and intraparietal sulcus) were shown to be related to executively demanding tasks, both verbal and nonverbal, consistent with implications of this area being part of a multiple-demand system (Duncan, 2010; Fedorenko et al., 2013; Humphreys and Lambon Ralph, 2017; Whitney et al., 2012). Ventral parietal areas (AG and SMG), in contrast, are associated with verbal and nonverbal tasks that engage more automatic processes (Humphreys and Lambon Ralph, 2017; Uddin et al., 2010; Vincent et al., 2008).

4.2. Neural network for Chinese lexical production

Chinese lexical production mainly activated left hemisphere frontal and subcortical regions – including IFG, MFG, motor cortex, SMA, insula, ACC, and caudate – as well as right cerebellum, regardless of the production mode (i.e., covert, overt, or handwritten) or cue stimulus (i.e., pinyin letters or character radicals). Handwritten character production (in contrast to baseline) showed more extensive activation of left motor cortex, and additional activation of left SFG (close to premotor cortex) and right insula, particularly for pinyin cue production, reflecting the greater motor demands of the task.

It should be noted that the baseline conditions employed in the present study was production of non-meaningful syllables or symbols, performed in the same production mode as its corresponding experimental condition (covert, overt, or handwritten). Therefore, brain activations observed for the reported contrasts do not include regions underlying basic sensorimotor production of sounds and strokes, and only include regions for the generation or retrieval of higher-level linguistic material. Activations for handwritten production without subtracting baseline implicated more widespread bilateral preCG, left SMA, and left postCG, confirming the greater involvement of sensorimotor areas for the manual motor aspects in handwriting.

The above results were obtained regardless of whether the production cue was pinyin letters or character radicals. There were, however, some differences between pinyin cue and radical cue production. In particular, production from pinyin cues (in contrast to radical) showed greater activation in motor-related, left inferior frontal, and dorsal parietal areas. Radical cue production, on the other hand, entailed more bilateral occipital activations. First, the greater involvement of motor-related areas in pinyin cue production is likely due to the fact that participants typically produced more words (and thus more motor actions) during pinyin than during radical cue production. Second,

Chinese word production from pinyin cues is likely to involve a phonological processing pathway, similar to the assembled processing method in alphabetic reading (Coltheart, 1981; Marshall and Newcombe, 1973; Patterson and Coltheart, 1987). Production from radical cues, on the other hand, likely entails an orthographic processing pathway, akin to the addressed processing method of Chinese character reading, using orthography-to-phonology transformations (Bi et al., 2009; Chen et al., 2002). Indeed, parietal regions have been associated with Chinese phonological processing (Wu et al., 2012), as well as with alphabetic reading compared to character reading (Chen et al., 2002; Law et al., 1991), with the IFG also playing a role in phonological encoding (Levelt et al., 1999; Roelofs, 2015). In contrast, orthographic processing for character reading has been found to activate bilateral or left occipital regions (Chee et al., 1999; Chen et al., 2002; Tan et al., 2001). Third, the production process from pinyin cues involves a greater number of levels of selection, including vowel (rime) selection, tone selection, and word form selection. Whereas, radical cue production, as mentioned, may bypass phonological information, and use an orthographic processing pathway to directly access word forms. Pinyin cue production, thus, requires greater inhibition of competing activations, further contributing to the greater involvement of domain-general inferior frontal and parietal areas under this condition.

There were also differences between overt and covert production. Overt production (in contrast to covert) activated more bilateral motor, somatosensory, and auditory cortices. According to the Directions Into Velocities of Articulators (DIVA; Guenther and Vladusich, 2012; Tourville and Guenther, 2011) model, overt speech entails articulatory movement, somatosensory perception of those movements, and auditory perception of the verbal productions, which activates motor, auditory, and somatosensory regions. In covert production, there is no perceptual feedback nor motor execution, and thus no activation in areas associated with these functions. Covert production, on the other hand, activated more bilateral frontal areas, along with right insula, bilateral ACC, and bilateral basal ganglia. Activation of bilateral SFG and ACC has been linked to the fact that the task requirement (generate words) and contextual information (do not articulate) are in conflict with each other to a certain extent (Basho et al., 2007). The activation of these areas may, therefore, reflect more nonlinguistic processing, such as inhibition (Fan et al., 2003) and attention- and motor-related conflict (Diedrichsen et al., 2006). The involvement of left IFG may be related to domain-general cognitive processes (Fedorenko et al., 2012), which may be engaged in language production for overcoming competition from the representation and selection of multiple words and meanings (Novick et al., 2009; Schnur et al., 2009). Together, these findings suggest that covert speech production is not simply overt production minus motor output, but may also involve non-language-specific cognitive components (Barch et al., 1999; Huang et al., 2002).

The Chinese lexical production tasks in the present study showed strong left hemisphere dominance, typical of language production, which can be seen both in the LIs and in the differences in percent signal change between left and right hemisphere ROIs. This confirms that word production tasks, particularly covert letter fluency tasks, are a robust means of examining functional language lateralization patterns in Chinese. The domain-general tasks, on the other hand, were more bilateral, with the stop-signal task showing a trend toward right lateralization, and the letter n-back task toward left lateralization. There was also a trend that more lateralized individuals show better verbal fluency performance, particularly for pinyin verbal fluency. Future research with a greater number of participants is needed to fully examine the relationship between functional language lateralization – particularly the degree (in addition to the direction) of lateralization – and language task performance (Van der Haegen and Cai, 2019).

The present results indicate that there is a core Chinese word production network (i.e., regardless of production mode or cue stimulus) comprising of regions mainly in left frontal, subcortical, and right cerebellar regions. Similar word production networks have been

observed in alphabetic languages. In particular, we compared the present results with that of an earlier study that involved healthy young adult participants performing covert letter fluency in Dutch (Cai et al., 2013). Covert letter fluency in Chinese and in Dutch showed similar patterns of activation, mainly in frontal, parietal, and subcortical regions, including left IFG, bilateral SMA, left preCG, left IPL, left SPL, left insula, right ACC, left basal ganglia, and right cerebellum (see Fig. 7). Other studies on word generation tasks in alphabetic languages have also reported similar activation patterns involving inferior frontal, motor-related, and basal ganglia areas (e.g., Birn et al., 2010; Costafreda et al., 2006; Henry and Crawford, 2004; Indefrey and Levelt, 2004; Li et al., 2017; Shao et al., 2014; Smirni et al., 2017; Tupak et al., 2012). Together, these findings indicate that a core network (left IFG, left motor, left SMA, left insula, left basal ganglia, and right cerebellum) represents a universal mechanism for lexical production – irrespective of language and (as mentioned) irrespective of production mode and cue stimulus – along with certain additional areas (left MFG, right SMA, left dorsal parietal, and bilateral ACC) involved under some production conditions (see Fig. 8 for an overview).

4.3. Limitations and future directions

A common limitation with fMRI word generation paradigms is the lack of behavioral data, especially since covert production mode is often used (Fu et al., 2002; Li et al., 2017). Even with our other modes of production, behavioral data could not be recorded since a) there was no MR-compatible voice-recording device available to record overt speech productions, and b) to avoid muscle movement artifacts, handwritten productions were rendered unreadable, as participants were asked to minimize stroke size and to write all characters in the same spot. Thus, behavioral performance for verbal fluency could only be recorded outside the scanner, where conditions are different (e.g., sitting vs. lying down, minimal noise vs. strong background noise). Such differences and the limited number of participants likely contributed to the lack of significant correlations found between brain activations and behavioral performance.

Secondly, although the present results showed involvement of brain regions also activated by domain-general cognitive tasks, the accumulation of evidence to date do not yet allow us to determine the precise role of domain-general cognitive functions in domain-specific language processes, such as the division of labor between domains and the specific conditions under which different domains may become involved. There are a number of possibilities for the way in which domain-general systems may be involved in domain-specific language processing (outlined below), each requiring further investigation. By exploring in greater depth the relationship between domain-general and domain-specific systems, we can gain greater insights into the manner in which domain-general cognitive functions participate in domain-specific processes such as language processing, and to develop theoretical frameworks for language processing that specify the division of labor across linguistic and cognitive mechanisms (Blank and Fedorenko, 2017; Fedorenko, 2014; McDowd et al., 2011).

One possibility is that domain-general brain regions are *necessary* in word production tasks, that is, without which task performance is substantially hampered or could not proceed. Future research could assess patients with relevant brain damage or those with cognitive control impairments, or utilize techniques such as transcranial magnetic stimulation (TMS) with healthy participants to investigate whether and how language production might be affected in the absence of certain brain functions. TMS is a noninvasive technique that temporarily alters cortical excitability. Inhibitory repetitive TMS (rTMS) produces a temporary “virtual lesion” in the area stimulated, allowing researchers to examine the causal role of the targeted region in the behavior of interest (Pascual-Leone et al., 2000). A study using inhibitory rTMS has already demonstrated a causal role for left lateral frontal cortex in letter fluency performance (Smirni et al., 2017). Future investigations are needed to

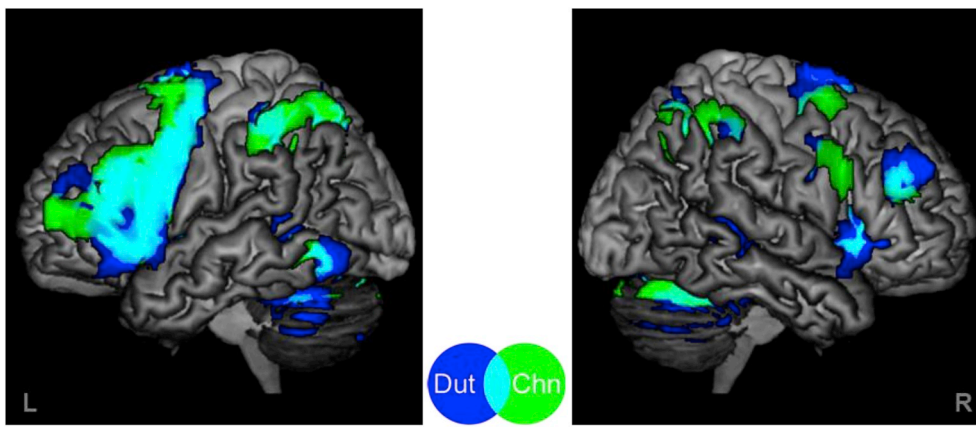


Fig. 7. Overlay of activations for Chinese lexical production (covert pinyin cue > baseline) and Dutch lexical production (covert letter cue > baseline; Cai et al., 2013). Green = Chinese unique. Blue = Dutch unique. Cyan = Chinese and Dutch overlap. Images thresholded at cluster level FWE rate $p < .05$. Overlay of images created using MRICron (<https://www.nitrc.org/projects/mricron/>). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

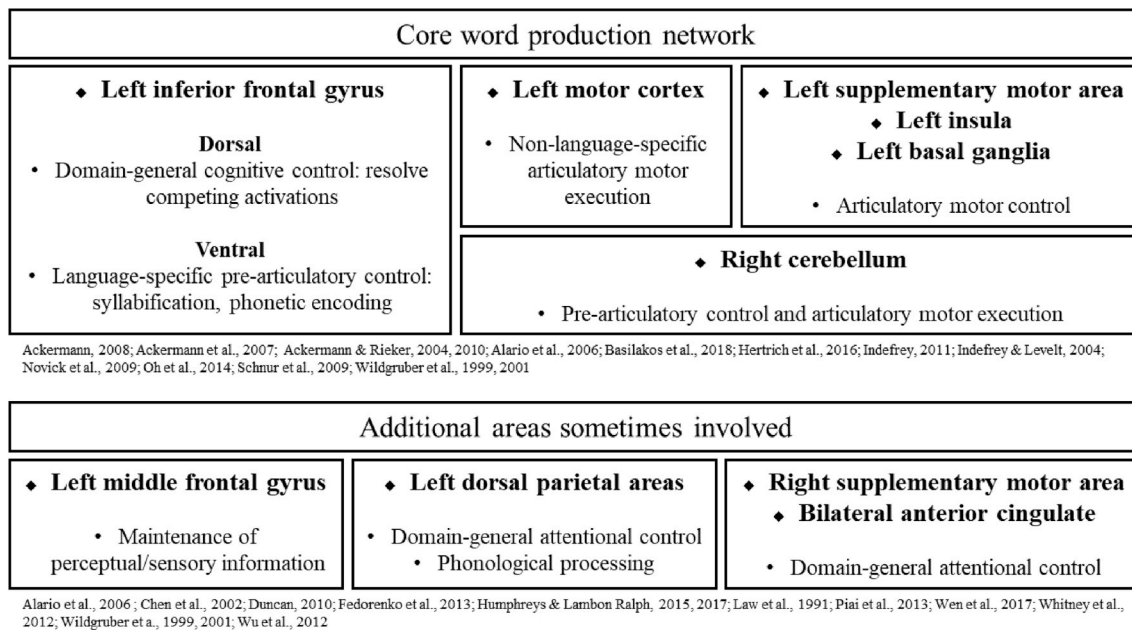


Fig. 8. Overview of core and additional areas involved in lexical production tasks.

examine the role of domain-general brain regions, and using more precise localization of stimulation sites (e.g., via task-related fMRI data). Another possibility is that domain-general cognitive functions play a *facilitatory*, but not a necessary, role in language production. Such a domain-general “multiple-demand” system may act as a flexible resource pool, allocable to and facilitating a wide range of cognitive processes, including some domain-specific processes such as face recognition and language processing (Fedorenko, 2014). However, it is unclear at present how such facilitations may be implemented, for example by providing an extra computational resource and thus increasing the processing speed of brain regions for domain-specific processes (Dehaene and Changeux, 2011; Nozari and Novick, 2017), or by providing an alternative pathway for task performance to proceed (Fedorenko, 2014; Ishkhanyan et al., 2019). A third possibility is that the involvement of domain-general systems is an *artifact* of the tasks used to study different aspects of language, and that under more naturalistic or task-free contexts such involvement may be reduced or disappear altogether (Blank and Fedorenko, 2017; Campbell and Tyler, 2018). This has been observed in language perception, including syntactic processing (Campbell and Tyler, 2018) and story comprehension (Blank and Fedorenko, 2017). Future work can explore more naturalistic methods for assessing language production to test this possibility.

4.4. Conclusions

Results of the present study support the involvement of domain-general executive functions – specifically response inhibition and working memory updating – in verbal-fluency-type word production tasks, although language-specific regions are also required. Areas activated during the working memory updating tasks appear to be involved to a greater extent than areas activated during response inhibition. Further, language-specific and domain-general regions are found to be closely neighboring subregions within the same broad brain area, corroborating previous distinctions of dorsal (domain-general cognitive functions) and ventral (language-specific functions) IFG. Additionally, left dorsal parietal regions appear to subservise a domain-general processing system, with its role in language production involving domain-general cognitive processing. Future work is needed to determine more precisely the relationship between domain-general and domain-specific systems, and whether domain-general mechanisms are necessary, as opposed to facilitatory or an artifact of the tasks used, for domain-specific functions. These efforts will help us to develop theoretical frameworks that define more clearly the division of roles across distinct domains and mechanisms.

In regard to the neural network for Chinese lexical production, a core

network of left frontal, subcortical, and right cerebellar regions was observed, with additional areas in bilateral frontal, left parietal, and bilateral ACC involved under some production conditions. Corroborating neural bases for production in alphabetic languages, these findings indicate that there is a universal network for lexical production, regardless of language, production mode, or cue stimulus type. Handwritten production mode, with additional manual motor requirements, showed greater involvement of sensorimotor areas. There were also differences between covert and overt modes. The areas engaged during overt production are associated with motor aspects of articulation and perception of somatosensory and auditory output, while those for covert production are associated with managing conflict arising from the task requirements of generating words but not articulating them.

Lastly, our findings support the use of letter verbal fluency tasks for assessing functional language lateralization, and in clinical and cognitive assessment settings. Compared to production from radical cues, production from pinyin letters showed greater relationship with domain-general executive functions (both in behavioral and in imaging results). In regard to production mode, although overt production is needed to obtain explicit test scores for behavioral assessment purposes, covert production mode may be more ideal for functional neural assessment, as it is likely to engage more domain-general cognitive components as well as help to minimize motion-related artifacts and lower-level sensorimotor activations. In regard to stimulus timing, the shorter blocks (with greater number of stimuli) typically used in imaging studies (e.g., 8 s) can still be useful in producing behavioral indicators, as performance on the imaging version and on the traditional behavioral version (1 min blocks) yielded strong correlations.

Declaration of competing interest

None to declare.

CRediT authorship contribution statement

Lily Tao: Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Miaomiao Zhu:** Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Qing Cai:** Conceptualization, Methodology, Writing - review & editing, Supervision.

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