Brain & Language 159 (2016) 118–126

Contents lists available at ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l

Tracking the time course of lexical access in orthographic production: An event-related potential study of word frequency effects in written picture naming

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ARTICLE INFO

Article history:
Received 11 May 2015
Revised 14 June 2016
Accepted 15 June 2016

Keywords:
Time course
Lexical access
Written word production
Written picture naming
Word frequency
ERPs

ABSTRACT

Previous studies of spoken picture naming using event-related potentials (ERPs) have shown that speakers initiate lexical access within 200 ms after stimulus onset. In the present study, we investigated the time course of lexical access in written, rather than spoken, word production. Chinese participants wrote target object names which varied in word frequency, and written naming times and ERPs were measured. Writing latencies exhibited a classical frequency effect (faster responses for high- than for low-frequency names). More importantly, ERP results revealed that electrophysiological activity elicited by high- and low frequency target names started to diverge as early as 168 ms post picture onset. We conclude that lexical access during written word production is initiated within 200 ms after picture onset. This estimate is compatible with previous studies on spoken production which likewise showed a rapid onset of lexical access (i.e., within 200 ms after stimuli onset). We suggest that written and spoken word production share the lexicalization stage.

1. Introduction

Existing theories of spoken language production assume that speech planning involves successive stages beginning with conceptual preparation and ending with articulation. Lexical access—the retrieval of words from the mental lexicon—constitutes a core processing stage of spoken production. This process is generally assumed to involve two processing components: the selection of a target lexical candidate from among coactivated alternatives (i.e., lexical selection) and the retrieval of its lexical-phonological representation (i.e., word-form encoding; e.g., Caramazza, 1997; Dell, 1986, 1988; Garrett, 1975, 1976; Levelt, 1989; Levelt, Roelofs, & Meyer, 1999). Over the past few decades, a vast amount of research has been dedicated to exploring lexical access during spoken production. By contrast, relatively less work has been directed at lexical access in written production. In the present study, we will focus on the latter issue.

According to a common view (e.g., Bonin, Chalard, Méot, & Fayol, 2002; Bonin & Fayol, 2000; Caramazza & Hillis, 1990; Chen & Cherng, 2013; Kandel, Peereman, Grosjacques, & Fayol, 2011; Rapp, Benzing, & Caramazza, 1997; Van Galen, 1991), spoken and written language production are carried out via shared higher-level cognitive processing, e.g., conceptual retrieval and lexical access. A number of studies have provided preliminary evidence to support this view (see Bonin et al., 2002; Bonin & Fayol, 2000 for behavioral studies; Brownsett & Wise, 2010 for neuroimaging evidence; Perret & Laganaro, 2012 for an electrophysiological study). Early evidence for the common-processing view came from behavioral studies. For instance, via a picture-word interference task with written or spoken object naming responses, Bonin and Fayol (2000) investigated effects of semantic and word-form overlap between picture names and distractor words, with the assumption that the two effects are located at the stage of lexical access. The reasoning was that if similar effects were found, this would indicate that the same processes are involved in the two modalities. In line with this prediction, the results showed that semantic overlap and word-form overlap exerted parallel effects in written and spoken production, which was taken to suggest that the two modalities of language production involve similar lexical access. In a further behavioral study, Bonin et al. (2002) aimed to identify crucial determinants of both written and spoken picture naming in a multiple regression analysis, and found common variables which contributed to naming latencies in both

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http://dx.doi.org/10.1016/j.bandl.2016.06.008
0093-934X/

production modalities (image variability, image agreement, age of acquisition, name agreement). These findings provide clear empirical support for the view that writing and speaking share cognitive processing stages before they diverge into modality-specific components (orthographic and phonological encoding, respectively).

More specific support for the view that written and spoken production share some processing comes from a recent electrophysiological study reported by Perret and Laganaro (2012) in which EEG activity associated with spoken and written picture naming was systematically compared. It was found that electrophysiological activity associated with naming in either modality was very similar until approximately 260 ms after stimulus onset, and diverged thereafter. The critical time point of divergence (i.e., 260 ms) matches a time estimate suggested in a meta-analysis of spoken word production by Indefrey and Levelt (2004, see also Indefrey, 2011) at which word-form encoding begins. Hence, the findings suggest that speaking and writing share conceptual and lexical-semantic stages, but that word-form encoding is modality-specific.

In the study reported below, we investigated the properties of written word production via a manipulation of lexical frequency. Frequency effects have been widely documented in the psychology of language (e.g., Forster & Chambers, 1973; Marslen-Wilson, 1990; Morton, 1969). Frequency effects also emerge consistently in tasks which require spoken word production (e.g., Alario et al., 2004; Jescheniak & Levelt, 1994). However, the exact locus of such frequency effects remains controversial. Some researchers hypothesized that word frequency effects may arise in recognition processes (Bates et al., 2003; Johnson, Paivio, & Clark, 1996), which receives support from the finding that frequency effects emerge in tasks that do not necessarily require lexical access, such as picture recognition and picture-word matching tasks (e.g., Kroll & Potter, 1984; but see Jescheniak & Levelt, 1994, Experiment 2 for failing to show such effects in a picture-word matching task). Other researchers have argued that frequency exclusively affects the stage of phonological encoding in speaking (e.g., Jescheniak & Levelt, 1994; Jescheniak, Meyer, & Levelt, 2003). In our reading, the current dominant view is that the word frequency effect in spoken production arises mainly at the level of lexical-semantic (“lemma”) access (Alario, Costa, & Caramazza, 2002; Almeida, Knobel, Finkbeiner, & Caramazza, 2007; Bonin & Fayol, 2002; Griffin & Bock, 1998). Word frequency effects in spoken word production have also been explored via EEG, and these studies have generally found such effects in relatively early time window, starting 150–200 ms after picture onset (Strijkers, Baus, Runnqvist, Fitzpatrick, & Costa, 2013; Strijkers, Costa, & Thierry, 2010; Strijkers, Holcomb, & Costa, 2011). Under the assumption that the onset of the word frequency effect arises during initial lexical processing, lexical access in speech production therefore initiates within 200 ms after stimulus presentation (see Strijkers & Costa, 2011 for a review).

In orthographic (rather than spoken) word production, effects of frequency also appear to emerge consistently in behavioral measures such as response latencies (e.g., Bonin & Fayol, 2000; Bonin, Fayol, & Chalard, 2001). However, to date there are very few EEG-based studies of orthographic production (e.g., Pinet, Hamamé, Longcamp, Vidal, & Alario, 2015). In a recent study, Baus, Strijkers, and Costa (2013) explored the electrophysiological correlates of lexical processing in a picture naming task with typed responses, and manipulated word frequency as an index of lexical access. They reasoned that if speaking and typing involve common lexical processing, the word frequency effect in writing should be expected to arise in a similar time window as in speaking, i.e., within 200 ms (see above). Contrary to this prediction, in their study a frequency effect in typed responses appeared in a much later time-window, i.e., 330–430 ms. The authors concluded that under the assumption that the frequency effect reflects lexical access, speaking and typing already diverge in processing at the start of lexical access. This inference, if correct, would conflict with those drawn from previous studies (see review above) according to which speaking and writing share higher-level processing stages including lexical access, and only diverge thereafter.

In the study below, we aimed to provide further evidence by focusing on the effects of word frequency in written, rather than typed, picture naming. In Baus et al. (2013) participants typed the names of pictures into a keyboard located on their lap, and response latencies (time interval between stimulus presentation and first key stroke) were relatively slow, with a mean of 1441 ms (the only study that we are aware of which has used a picture naming task with typed responses reported by Pinet et al., 2015, showed average latencies of 1084 ms). By contrast, numerous studies on handwritten word production (e.g., Bonin, Fayol, & Peereman, 1998; Perret & Laganaro, 2013; Qu, Damian, Zhang, & Zhu, 2011) which have resulted in latencies (interval from stimulus presentation to first contact of pen with writing tablet) similar to those found in spoken picture naming (i.e., 800–1000 ms). Indeed, Perret and Laganaro (2013) recently compared latencies of spoken and written responses directly, and found that written responses were somewhat (~100 ms) slower when writers could monitor their written responses. However, when writers were prevented from looking at their responses, spoken and written latencies were virtually identical, leading to the conclusion that cognitive processes associated with spoken and written responses are very similar, and the slower responses in written responses when writers monitor their responses arises from eye movements between the screen and the writing surface.

A plausible reason for slower responses in typing compared to handwriting (and speaking) is that handwriting is usually learned early in life, whereas typing is a skill typically acquired much later, and with considerable individual variability in the achieved performance levels. In our study, participants named pictures via handwritten responses and were instructed to avoid looking at their writing hand in order to minimize movement artifacts in the EEG recording. Based on Perret and Laganaro's work, we therefore expected latencies which are in line with those from previous spoken (and written) production tasks (i.e., <1000 ms).

We recruited native Mandarin speakers for our study. Of course, the orthographic system differs substantially between languages with non-alphabetic and alphabetic scripts. However, there is no reason to suspect that this should affect relatively “early” processing stages such as lexical access. Indeed, behavioral frequency effects in (spoken) picture naming have been reported with Chinese participants (e.g., Caramazza, Costa, Miozzo, & Bi, 2001; Janssen, Bi, & Caramazza, 2008) which are of comparable size to those obtained with speakers of Western languages (e.g., Jescheniak & Levelt, 1994).

2. Results

2.1. Behavioral results

As shown in Fig. 1B, written response latencies exhibited a word frequency effect of 36 ms, with shorter latencies for high-frequency words (851 ms) than low-frequency word (887 ms). Latencies were analyzed using a linear mixed-effects model (Baayen, Davidson, & Bates, 2008; Bates, 2005). Model fitting was carried out by initially specifying a model that only included intercepts for participants and items as random effects. An enriched model which additionally included the fixed factor word frequency showed a significantly improved fit, $\chi^2(1, N = 2614) = 9.53$, $p < 0.001$. The linear mixed-effects model revealed a significant

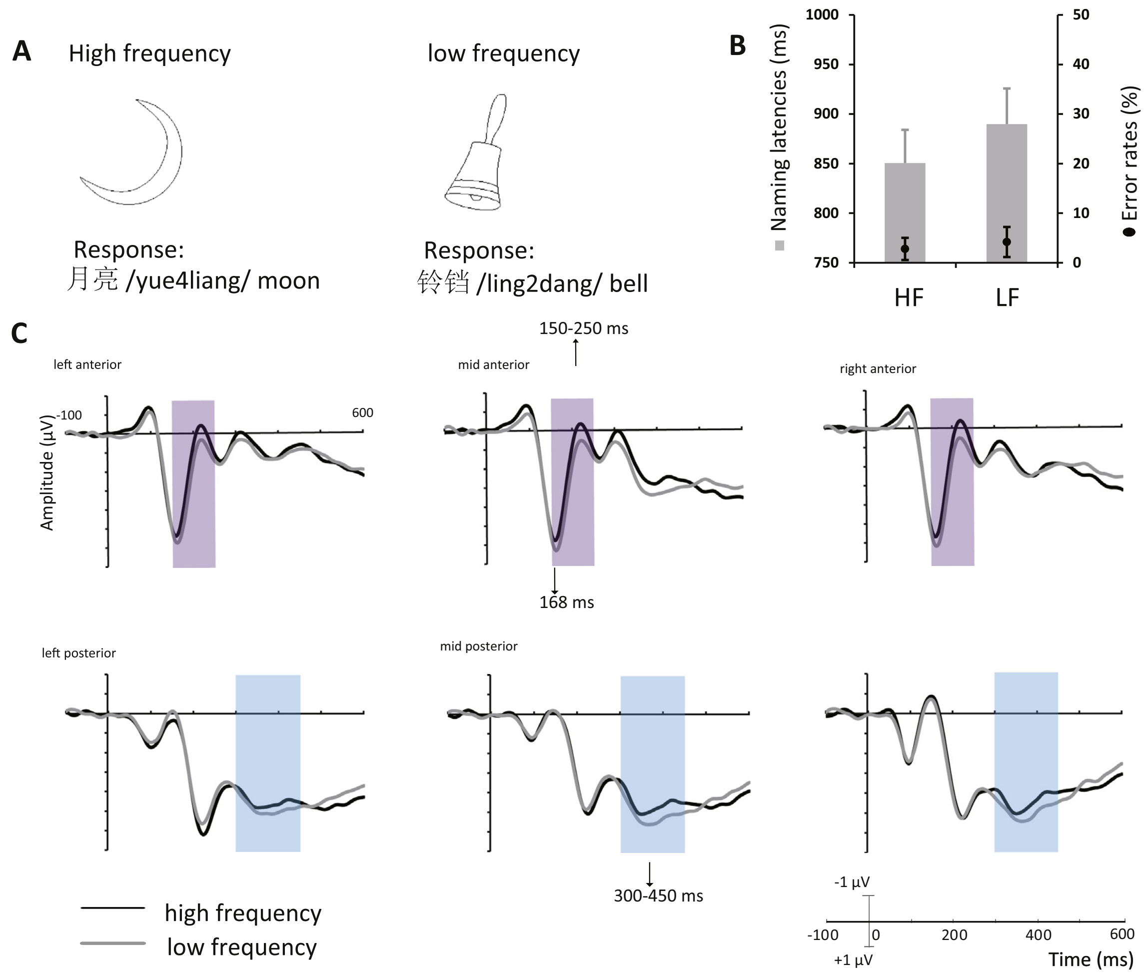

Fig. 1. (A) Twenty-two participants were asked to write down the names of one hundred fifty pictures, half of which had high-frequency and the other half had low-frequency names. (B) Behavioral data show a classical word frequency effect on naming latencies (gray bars, left axis) or error rates (right axis). Error bars represent 95% confidence intervals. LF stands for low frequency items and HF for high frequency items. (C) Grand average ERPs from 22 native Chinese speakers for the high-frequency (black line) and low-frequency (gray line) conditions at six ROIs: left-anterior (electrodes: F7, F5, F3, FT7, FC5, FC3), mid-anterior (F1, FZ, F2, FC1, FCZ, FC2, C1, CZ, C2), right-anterior (F4, F6, F8, FC4, FC6, FT8), left-posterior (CP5, CP3, P5, P3, PO7, PO5), mid-posterior (CP1, CPZ, CP2, P1, PZ, P2, PO3, POZ, PO4, O1, OZ, O2), and right-posterior (CP4, CP6, P4, P6, PO6, PO8). The onset of a picture is represented by 0 ms. Low-frequency ERPs were significantly more positive than high-frequency ERPs in two time windows (150–250 ms, blue shading, and 300–450 ms, blue shading). Low-frequency and high-frequency ERPs diverged from each other beginning at 168 ms after picture onset, indicating early lexical access during written production.

word frequency effect ($b = 38.19$, $SE = 12.20$, $t = 3.13$, $p = 0.002$).[1,2] Therefore, the final model included word frequency as the fixed effect and intercepts for participants and items as random effects.

A parallel analysis was conducted on the errors, but a binomial family was used because of the binary nature of the responses (Jaeger, 2008). Adding the factor of word frequency marginally significantly improved the fit, Wald $Zs = 1.81$, $ps = 0.070$, reflecting a word frequency effect, with fewer errors for high-frequency words (2.9%) than low-frequency words (4.1%).

2.2. Onset latency analyses

ERPs for high and low-frequency conditions were compared by running t-tests at every sampling point (every 2 ms) starting from the picture presentation over all electrodes. Fig. 2 presents significant p-values resulting from the t-tests at each sampling point across all electrodes. Onset latency analyses were based only on one representative anterior-central electrode (Cz) and one representative posterior electrode (Pz) respectively where significant word frequency effects emerged in the mean amplitude analysis. Onset latency analyses (Guthrie & Buchwald, 1991) suggested that for our data, differences between high- and low-frequency conditions could be considered reliable when at least a sequence of 21 consecutive data points (42 ms) for Cz, and 17 consecutive data points (34 ms) for Pz, exceeded the 0.05 significance level. Given that there were >40 consecutive significant t-values (80 ms) for both Cz and Pz in our case, it can be concluded that the effects at the two electrodes were clearly statistically significant. T-tests showed that ERPs associated with high- and low-frequency

[1] According to the argument highlighted in Barr, Levy, Scheepers, and Tily (2013) one should specify a "maximum model" by including not only by-participant and by-item adjustments, but also allow for adjustments to the slope of each critical within-participants/items variable. Because frequency is manipulated within-participants but between-items, we specified slope adjustments only for participants but not for items. However, this model returned a correlation of 1.00 between intercept and slope for the critical variable, which indicates that the model has been overparameterized (Baayen et al., 2008) and the simpler model without slope adjustments is preferable.

[2] As described under "Section 4.5", data were filtered according to a relatively strict cutoff on latencies (trials with latencies <600 ms or >1500 ms were excluded). We additionally re-analyzed written latencies with cutoffs which are more typical of behavioral studies (latencies <250 ms or >2500 ms were excluded). The word frequency effect was preserved, with shorter latencies for high-frequency words (864 ms) than low-frequency words (912 ms).

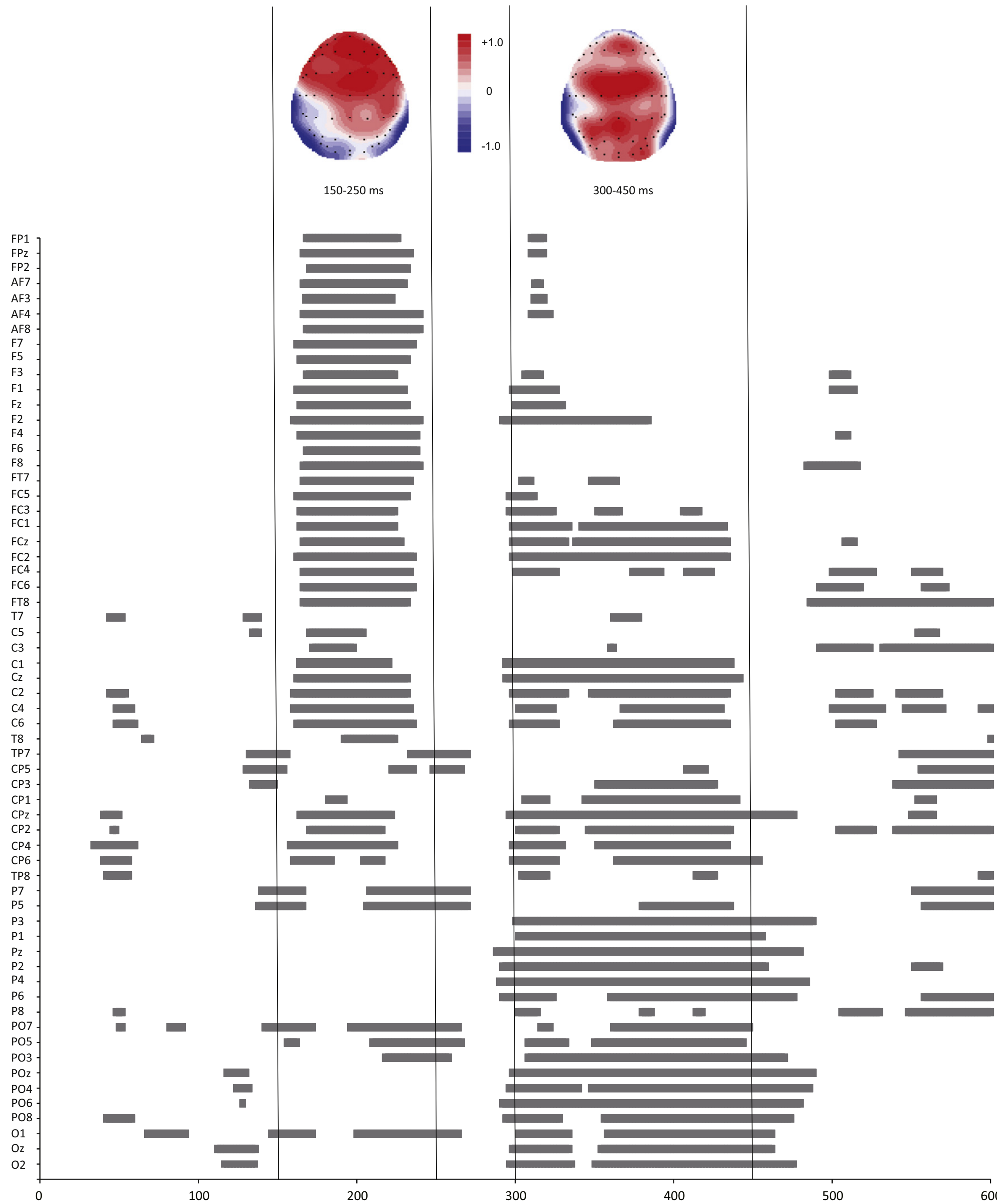

Fig. 2. P values resulting from *t*-tests at each sampling point starting from the picture presentation across all 62 channels. Gray points correspond to those p-values below 0.05. Topographic maps corresponding to the difference waves between low- and high-frequency conditions in the 150–250 ms and 300–450 ms time windows. The vertical lines depict the time windows used for mean amplitude analyses.

conditions started to diverge significantly from each other at 168 ms after picture presentation at Cz, and at 352 ms at Pz.

2.3. Mean amplitude analyses

Grand average ERP waveforms are displayed in Fig. 1C for the two conditions and six regions of interests chosen for the analysis. The main results of the omnibus ANOVA, conducted separately for each of the 6 time intervals, are as follows (see details in Table 1). Neither the main effect of word frequency nor interactions involving word frequency were significant in the **baseline interval** ($ps > 0.628$). In the early time window (**0–150 ms**), neither the main effect of word frequency nor interactions involving word frequency were significant ($ps > 0.086$). In the critical **150–250 ms** time window, the interaction between word frequency and anteriority was significant ($F(1,21) = 11.04$, $p = 0.003$), reflecting more positive amplitudes for low-frequency words compared to high-frequency words in the anterior regions ($t(21) = -2.43$, $p = 0.024$), but not in the posterior regions ($t < 1$, $p = 0.623$). Pairwise comparisons at each ROI revealed a significant effect of word frequency in the left anterior, $t(21) = -2.22$, $p = 0.037$, mid anterior, $t(21) = -2.14$, $p = 0.044$, and right anterior, $t(21) = -2.63$, $p = 0.016$.

Table 1
Summary of omnibus ANOVA and analyses of individual ROIs in six time windows.

	Time windows					
	−100–0	0–150	150–250	250–300	300–450	450–600
	p	*p*	*p*	*p*	*p*	*p*
ANOVA						
wf	0.770	0.503	0.141	0.824	0.071	0.212
wf × ant	0.628	0.311	**0.003****	0.218	0.620	0.905
wf × lat	0.998	0.266	0.135	0.619	**0.049***	0.854
wf × ant × lat	0.703	0.087	0.072	0.430	**0.035***	**0.042***
Effect of word frequency at individual ROIs (t-test)						
Left anterior	0.593	0.409	**0.037***	0.492	0.450	0.734
Mid anterior	0.856	0.315	**0.044***	0.501	0.103	0.384
Right anterior	0.910	0.354	**0.016***	0.565	0.552	0.161
Left posterior	0.404	0.346	0.098	0.158	**0.050***	0.146
Mid posterior	0.957	0.889	0.744	0.588	**0.006****	0.386
Right posterior	0.898	0.423	0.497	0.996	**0.009****	0.322

Note. wf = word frequency; lat = laterality; ant = anteriority.
* $p \leqslant 0.05$.
** $p \leqslant 0.01$.

In the **250- to 300-ms** time window, neither the main effect of word frequency nor its interactions were significant (*ps* > 0.218). In the **300- to 450-ms** time window, the word frequency × anteriority interaction was significant, $F(2,42) = 3.25$, $p = 0.049$, and the frequency × anteriority × laterality interaction was significant, $F(2,42) = 3.64$, $p = 0.035$. Follow-up analyses demonstrated that the word frequency effect was significant in the posterior regions ($t(21) = -2.92$, $p = 0.008$), as a result of more positive amplitudes for low-frequency words compared to high-frequency words, but not significant in the anterior regions ($|t| < 1.14$, $p > 0.268$). Pairwise comparisons at each ROI showed a significant effect in the left-posterior, mid-posterior, and right-posterior regions ($|t| > 2.06$, *ps* < 0.050). In the **455- to 600-ms** time window, the only significant effect involving the factor frequency was the frequency × anteriority × laterality interaction, $F(2,42) = 3.42$, $p = 0.042$. However, no significant effect was found when each ROI region were analyzed separately (*ps* > 0.146).

3. Discussion

The present study measured behavioral responses and ERPs of the word frequency effect during written picture naming to elucidate the time course of lexical access in written word production. The behavioral results showed a classical word frequency effect, with shorter response latencies for pictures with high-frequency names than that with low-frequency names (Bonin & Fayol, 2002; Jescheniak & Levelt, 1994; Oldfield & Wingfield, 1965). More critically, the ERP results revealed a word frequency effect in the time windows of 150–250 and 300–450 ms, starting at 168 ms after picture onset, with low-frequency responses eliciting more positive amplitudes than high-frequency words. Based on these findings we propose that writers begin lexicalizing their responses within 200 ms after picture onset, a time frame which is similar to the one typical of spoken word production (see below). Hence our findings provide evidence for the position that lexical access is shared between speaking and writing.

The latency of 168 ms found in the present study is roughly consistent with the estimated time window of lexical ("lemma") access in spoken production (175–250 ms) by Indefrey and Levelt (2004), and with previous electrophysiological studies in the spoken modality. For instance, using magnetoencephalography (MEG), Maess, Friederici, Damian, Meyer, and Levelt (2002) explored the time course of lexical retrieval by investigating a "semantic context effect", i.e., picture naming responses are slower when naming exemplars from the same category than from mixed categories. This effect is commonly assumed to reside at the level of lexical access (see e.g., Damian, Vigliocco, & Levelt, 2001; Kroll & Stewart, 1994). The results revealed significant differences between the same- and mixed category conditions in a similar time window, 150–225 ms after picture onset. In an EEG study, Costa, Strijkers, Martin, and Thierry (2009) manipulated the ordinal position of objects belonging to the same semantic category, and measured the electrophysiological correlate of the cumulative semantic interference effect (CSIE) as a proxy for lexical selection in spoken production. The CSIE refers to the effect that object naming responses grow increasingly slower with repeated retrieval of exemplars from the same semantic category. Costa et al. observed significant ERP amplitude modulations associated with the CSIE, as reflected by positive correlations between naming latencies and ERP amplitudes, which began as early as 208 ms after picture onset. In a series of EEG spoken naming studies, Strijkers and colleagues manipulated word frequency of picture names in an overt picture naming task and observed that manipulation of word frequency of picture names yielded ERP effect within 180 ms after picture presentation (172 ms in Strijkers et al., 2010; 152 ms in Strijkers et al., 2011; 148 ms in Strijkers et al., 2013; see Strijkers & Costa, 2011 for a review). In the present study which manipulated the same variable but used a different production modality, we observed an EEG effect in very similar time frame. Based on these findings, we argue that spoken and written language production systems share lexical access.

The word frequency effect which emerged in our ERPs coincides with a positive-going ERP component (P2) which has typically been observed in the spoken modality (e.g., Strijkers et al., 2010, 2011, 2013), with low-frequency responses eliciting more positive amplitudes compared to high-frequency responses. In the spoken domain, this component has been shown to be sensitive to a range of lexical variables, and is hypothesized to reflect the ease of lexical access, with less positive (i.e., lower amplitude) associated with easily accessible representations (high-frequency words in this case) and more positive (i.e., greater amplitude) associated with less accessible representations (low-frequency words in this case) (Costa et al., 2009; Strijkers et al., 2010). Our findings extend the P2 component to the written modality. However, it is worth noting that earlier studies (e.g., Strijkers et al., 2010, 2011, 2013) showed that the P2 component was mainly distributed posteriorly, whereas our ERP word frequency effect result was mainly distributed across anterior and central regions.

The present findings also provide important insights into the locus of the word frequency. In spoken production, a large amount of existing research has been dedicated to identifying the stage at which frequency effects reside, and as briefly summarised in

Section 1, this issue remains somewhat controversial. Comparatively little research has been directed at the source of frequency effects in written production. In the present study, we found that the word frequency effect was present in the time windows of 150–250 ms and 300–450 ms, which are roughly consistent with lexical selection and word-form encoding respectively in the meta-analysis by Indefrey and Levelt (2004). It is therefore possible that the word frequency effect in our results affected both lexical selection ("lemma access") and word-form encoding, rather than exclusively affecting the stage of word-form encoding. This inference is consistent with previous reports on spoken word production (see Strijkers et al., 2010). However, in a seminal MEG study on frequency effects in spoken production, Levelt, Praamstra, Meyer, Helenius, and Salmelin (1998) argued that if an experimental manipulation such as word frequency affects the temporal duration of a particular processing stage, then all subsequent processing stages will also be shifted in time by a constant amount of time. Based on this logic, the frequency effect in our study which emerge in the "early" point in time (150–250 ms, so probably residing at the "lemma" stage) might desynchronise processing at later stages, leading to the emergence of frequency effects in the EEG signals under these stages as well. Further research is required to investigate this possibility. However, our findings extend word frequency as an index of lexical access into the written modality, and in doing so, validate the use of the word frequency effect to constrain theories of lexical access in written production.

As reviewed above, our present findings concerning the time course of lexical access are consistent with previous studies on speaking, but the time course of the frequency effect (starting at 162 ms after picture onset) diverges from the one reported by Baus et al. (2013) for typed responses (which began around 350 ms after picture onset). What could explain this discrepancy? A first possibility is that there are fundamental differences between handwriting and typing with regard to lexical access. However, on the face of it it seems unlikely that output modality (writing vs. typing) of an orthographic production task should impact on high-level processing involved in lexical access. A second possibility arises from a substantial difference in overall response speed: average response latencies in Baus et al. (1440 ms) were much slower than that in our study (871 ms), and this could have generated a "late" ERP frequency effect in the former compared to the latter results. This is not impossible, and future studies should try to replicate Baus et al.'s study with participants which are more skilled in typing so that overall latencies are better matched between typing and writing (or perhaps, both response modalities are tested with the same group of participants). Note that although a number of EEG studies on spoken word production have suggested that the onset of lexical access is unaffected by the overall speed of response (e.g., Strijkers et al., 2010, 2011, 2013), it has been documented in recent ERP study that the between-subject variability in the speed of single word production is largely attributable to the lexical selection stage (Laganaro, Valente, & Perret, 2012).

Furthermore, Baus et al. tested Spanish speakers whereas we used speakers of Chinese Mandarin. Could the different orthographic script (alphabetic vs. non-alphabetic) associated with the two languages account for the difference in overall latencies? Very little relevant work exists on the characteristics of non-alphabetic orthographic word production (e.g., Chen & Cherng, 2013) but again it seems unlikely that lower-level characteristics of orthographic encoding such as planning units (letters vs. strokes/radicals) could influence the time course of a high-level stage such as lexical access.

A final possible reason for the discrepancy in time course between the present and Baus et al.'s (2013) findings is that a potentially important variable, namely age-of-acquisition (AoA), or the average age at which a word has been learned, affected the results. Over the last few decades, AoA has emerged as a major determinant of latencies in various language tasks (e.g., Ellis & Lambon Ralph, 2000; Morrison, Ellis, & Quinlan, 1992), including spoken (e.g., Barry, Morrison, & Ellis, 1997) and written (Bonin et al., 2001) word production. AoA shows a substantial negative correlation with frequency, and this confound is difficult, although not impossible, to avoid. For Baus et al.'s Spanish materials, English translation equivalents showed AoA ratings which were significantly earlier for high-frequency than for low-frequency words ($p = 0.016$; AoA ratings were obtained from Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012, and estimated age at which words had been learned). Our own materials were statistically matched on Chinese AoA ratings (Liu, Hao, Li, & Shu, 2011), but on English translation equivalents of target words, the AoA confound weakly re-emerged ($p = 0.095$). Interestingly, Perret, Bonin, and Laganaro (2014) recently manipulated AoA in spoken and written object naming while holding frequency constant, and found an AoA effect in a time window approximately 400 ms post picture onset. This could imply that effects which appear in relatively "late" time windows (such as the effect in Baus et al., 2013, and to some extent the late portion of the effect in our current study) might be attributed to AoA rather than frequency. We are currently conducting EEG-based object naming experiments in which frequency and AoA are factorially crossed, and based on the available evidence we predict that frequency effects will precede AoA effects in the time signature of EEG responses.

On a broader level, our findings, in conjunction with the previous EEG studies on word frequency effects in spoken production (see Section 1) highlight communalities, rather than differences, between different forms of word production. Indeed, it seems to be the case that spoken and orthographic forms of production share higher-level cognitive planning stages. If word frequency effects reliably index the stage of "lemma" access, and lemmas are shared between different production forms, then a similar time course of frequency effects in EEG is predicted – as is empirically the case. Only after access to abstract lemmas do different forms of production diverge into modality-specific preparation patterns. In this sense, our results converge with Perret and Laganaro's (2012) postulation of "similar processes up to lexical selection and different networks underlying the encoding of surface forms (respectively phonological and orthographic)." (p. 70).

In summary, it is a common assumption that spoken and written word production share some processing stages (Rapp, Benzing, & Caramazza, 1997) but the exact point at which the two response modalities diverge remains controversial. Our study shows that lexical access in written picture naming is initiated within 200 ms after picture presentation. The similarity to parallel findings with spoken responses suggests that common lexical retrieval underlies written and spoken word production.

4. Method

4.1. Participants

Twenty-two native Chinese Mandarin speakers (11 females, mean age 20.5 years) participated and were compensated for their time. All participants were right-handed, with normal or corrected-to-normal vision and no history of neurological or language problems.

4.2. Materials

One hundred and thirty-eight black and white drawings were selected from the picture set of Liu et al. (2011; see Fig. 1A for example). All picture names were disyllabic and hence consisted of two orthographic characters in Chinese. The independent variable was word frequency, as determined by the Chinese Linguistic Data Consortium (2003) norms. Half of the pictures had high-frequency names and the remaining half had low-frequency names. Frequency values were significantly higher for high-frequency (all >4.5/per million, mean = 15.5 per million, $SD = 24.81$) than for low-frequency words (all <1.5/per million, mean = 0.86 per million, $SD = 0.37$; $t(136) = 4.9$, $p < 0.001$). Words in both conditions were matched for the following variables: word length in number of character; stroke number of first character, second character, and two-character word; image variability; image agreement; concept familiarity; visual complexity; name agreement in percentage; concept agreement, and rated age of acquisition (Liu et al., 2011). Stimuli of both conditions were also matched for neighborhood density and frequency of the first syllable, as determined by the Chinese Linguistic Data Consortium (2003) norms. A further 12 pictures were added as fillers.

Each participant was presented with three blocks of 50 trials within each block, for a total of 150 trials.

4.3. Procedure

Stimuli were presented using E-Prime 1.1 software (Psychology Software Tools, Pittsburgh, PA). Written responses were recorded using an Intuos4 graphic tablet and inking pen (Wacom, Kazo-shi, Japan), and an A4 sheet of paper attached to the tablet. Participants were tested individually in a sound-attenuated lab. Participants were first asked to familiarize themselves with the experimental stimuli by viewing them in a booklet, with the expected name printed underneath each picture. Subsequently, participants were told that they would see the pictures presented in the center of the computer screen, and their task was to write down picture names as quickly and accurately as possible. Participants were instructed to lift the pen very slightly from the answering sheet so that response could be given as fast as possible; they should not drop the pen on the sheet before identifying the response. They were asked to keep gazing at the screen during writing and refrain from looking at what they had written (i.e., visual feedback was prevented) in order to minimize movement artifacts in the EEG recording. Compliance with these instructions was ensured before the experiment began.

In a subsequent practice block, 10 pictures which were not from the set of target words were presented. After the practice, three experimental blocks of 50 trials were presented. There were short breaks between blocks, and the next block started after participants indicated that they were ready to continue. On each trial, participants saw a sequence consisting of a fixation cross (500 ms), a blank screen (500 ms), and a picture. The picture disappeared once the participant initiated a response on the graphic tablet, or after a time-out of 4000 ms. The intertrial interval was 6000 ms. The experimental task session lasted approximately 30 min. The entire experiment lasted about 2 h.

4.4. EEG recordings and analysis

The electroencephalogram (EEG) was recorded with 64 electrodes secured in an elastic cap (Electro Cap International) using Neuroscan 4.3 software. The vertical electrooculogram (VEOG) was monitored with electrodes placed above and below the left eye. The horizontal EOG (HEOG) was recorded by a bipolar montage using two electrodes placed on the right and left external cantus. The left mastoid electrode served as reference. The EEG data were re-referenced off-line to the average of both mastoids. All electrode impedances were kept below 5 kΩ. Electrophysiological signals were amplified with a band-pass filter of 0.05 and 100 Hz (sampling rate 500 Hz) and filtered off-line using a 0.03 Hz high-pass filter and 20 Hz low-pass filter. Epochs containing artifact signals below/above ±100 μV were rejected. The EEG was segmented into 700 ms epochs relative to picture onset that included a 100 ms pre-stimulus baseline and a 600 post-stimulus interval.

4.5. Data analysis

Trials with incorrect responses (3.5%) and trials with writing onset latencies faster than 600 ms or slower than 1500 ms (9.8%) were excluded from the behavioral and ERP analyses. For the ERP analysis, a further 3.0% of trials were excluded due to artifacts. In total, ERP analyses were based on an average of 58 segments per condition (high frequency: 59, low frequency: 57).

Two types of analyses were conducted on the ERP data. First, onset latency analysis was performed, with the aim of identifying the latency at which the ERPs of the two conditions (high- vs. low-frequency) started to diverge significantly from each other. To protect against problems associated with multiple comparisons, we performed onset latency analyses using a method developed by Guthrie and Buchwald (1991) (see e.g., Costa et al., 2009; Strijkers et al., 2010; Thierry, Cardebat, & Démonet, 2003 for use of this method in recent studies). This method assumed difference potential waveforms possess a first-order autoregressive structure with sampling points statistically dependent and used this assumption to generate how long an interval of consecutive significant points can be expected by chance (i.e., "the critical run length for determining statistical significance", the duration of interval that you count as significant) via computer simulations. Computer-simulated estimates of such critical run length were based on 1000 repetitions for each of several autocorrelation coefficients, sample sizes, and sampling interval length. If the observed number of consecutive significant time points is larger than the critical run length, it would indicate a statistically significant interval. We took the onset point of a sequence of consecutive significant points as the onset of the word frequency effect.

Second, mean amplitudes analyses were conducted. We selected six time windows for analyses (−100 to 0, 0–150, 150–250, 250–300, 300–450, 450–600 ms) based on a visual inspection of the *t*-test figure (i.e., Fig. 2), combined with a consideration of temporal estimates provided by Indefrey and Levelt (2004) and Indefrey (2011). Fig. 2 suggests "breakpoints" around 150 ms (where largely frontal effects begin to appear) and 250 ms (where frontal effects disappear), around 300 ms (where largely posterior effects begin to emerge) and at 450 ms (where they disappear). Note that the resulting time windows to some extent converge with the time estimates provided by Indefrey and colleagues concerning the temporal dynamics of lexical access in spoken production (onset of "lemma access": 175–200 ms; onset of word form encoding: 250–275 ms; offset of word form encoding: ∼450 ms). To provide a comprehensive picture of ERP effects, we conducted statistical analyses using six regions of interest (ROIs): left-anterior (electrodes: F7, F5, F3, FT7, FC5, FC3), mid-anterior (F1, FZ, F2, FC1, FCZ, FC2, C1, CZ, C2), right-anterior (F4, F6, F8, FC4, FC6, FT8), left-posterior (CP5, CP3, P5, P3, PO7, PO5), mid-posterior (CP1, CPZ, CP2, P1, PZ, P2, PO3, POZ, PO4, O1, OZ, O2), and right-posterior (CP4, CP6, P4, P6, PO6, PO8). In this ROI analysis that enabled us to probe the scalp distribution of ERP differences, mean amplitudes from each time window were entered into a $2 \times 2 \times 3$ repeated measures ANOVA with factors word frequency (high/low), anteriority (anterior/posterior), and laterality (left/middle/right). Greenhouse-Geisser correction was applied where appropriate, to control for violations of the sphericity assumption (original degrees of freedom are reported). All main effects and interactions involving the factor word frequency that were significant at $p < 0.05$ levels will be discussed.

Acknowledgments

We acknowledge Mengsi Wang for help in data collection. This work was supported by the Scientific Foundation of Institute of Psychology, Chinese Academy of Sciences, under Grant No. Y3CX132005, and the National Natural Science Foundation of China, No. 31400967, to the first author.

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