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Balanced bilinguals favor lexical processing in their opaque language and conversion system in their shallow language

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Referred to as orthographic depth, the degree of consistency of grapheme/phoneme correspondences varies across languages from high in shallow orthographies to low in deep orthographies. The present study investigates the impact of orthographic depth on reading route by analyzing evoked potentials to words in a deep (French) and shallow (German) language presented to highly proficient bilinguals. ERP analyses to German and French words revealed significant topographic modulations 240–280 ms post-stimulus onset, indicative of distinct brain networks engaged in reading over this time window. Source estimations revealed that these effects stemmed from modulations of left insular, inferior frontal and dorsolateral regions (German > French) previously associated to phonological processing. Our results show that reading in a shallow language was associated to a stronger engagement of phonological pathways than reading in a deep language. Thus, the lexical pathways favored in word reading are reinforced by phonological networks more strongly in the shallow than deep orthography.

1. Introduction

Growing evidence suggests that neurocognitive processes involved in word recognition and reading vary depending on internal and external factors. In addition to age (e.g. Wu et al., 2014), language proficiency (e.g. Dehaene et al., 2010; Newman, Tremblay, Nichols, Neville, & Ullman, 2012) or other characteristics of the reader, word features including their regularity or lexicality have been demonstrated to modulate the brain networks involved in reading (e.g. Jobard, Crivello, & Tzourio-Mazoyer, 2003). Another factor having received much less attention is the orthographic depth, i.e. the consistency of grapheme/phoneme patterns of a language. However, a better understanding of the impact of orthographic depth on the underlying brain networks would be of particular interest since the consistency of grapheme/phoneme correspondences has been shown to critically influence literacy acquisition (e.g. Ellis & Hooper, 2001; Goswami, 1998; Lallier, Carreiras, Tainturier, Savill, & Thierry, 2013), reading performance (Seymour, Aro, & Erskine, 2003) and the emergence of language-related disorders such as dyslexia (Goswami, 1998; Paulesu et al., 2001; Wheat, Cornelissen, Frost, & Hansen, 2010).

The Dual Route Cascade Model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; for a review see Jobard et al., 2003) assumes that after letter identification, word reading processing may follow two pathways, differentiating in the way graphemes and phonemes are being mapped. The predominant (i.e. not exclusive) engagement of each pathway would depend on the degree of the regularity, lexicality and/or familiarity of the word being read. Both routes have been proposed to rely on common structures, such as the left occipito-temporal region, which has been found to be activated in both phonological (non-lexical; Binder, Medler, Desai, Conant, & Liebenthal, 2005; Kronbichler et al., 2004; Mechelli et al., 2004; Xu et al., 2001) and lexical processing (Binder et al., 2005; Fiebach, Friederici, Muller, & von Cramon, 2002; Ischebeck et al., 2004; Rissman, Eliassen, & Blumstein, 2003).

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Regular and unfamiliar word or non-word reading may preferentially rely on phonological pathways, where each grapheme is sequentially mapped to its corresponding phoneme. Neural correlates of phonological processing have most commonly been identified within superior temporal (Graves, Grabowski, Mehta, & Gupta, 2008; Jobard et al., 2003), supramarginal (Graves et al., 2008; Jobard et al., 2003; Roux et al., 2012), insular (Binder et al., 2005; Fiez, Balota, Raichle, & Petersen, 1999; Herbster, Mintun, Nebes, & Becker, 1997) and inferior frontal regions/pars opercularis; BA44; e.g. Jobard et al., 2003; Nixon, Lazarova, Hodinott-Hill, Gough, & Passingham, 2004; Binder et al., 2005).

In contrast, irregular and familiar word reading may preferentially involve lexical pathways, where phonological word forms are retrieved from memory structures, i.e. from orthographic and their corresponding phonological lexical entries. Lexico-sematic processing has most commonly been linked to bilateral inferior-middle temporal (Ischebeck et al., 2004; Jobard et al., 2003) and inferior frontal regions/pars triangularis; BA 45; Fiebach et al., 2002; Jobard et al., 2003; Binder et al., 2005; Rissman et al., 2003; Ischebeck et al., 2004).

The pathway involved in mapping graphemes to phonemes may not only be influenced by the regularity, lexicality and familiarity of a word but also by the orthographic depth of a language. The orthographic depth refers to the degree of consistency of grapheme/phoneme correspondences and varies across languages from high in shallow orthographies to low in deep orthographies. The Orthographic Depth Hypothesis (Katz & Feldman, 1983; revised by Katz & Frost, 1992) posits that reading shallow orthographies (e.g. German and Italian) with consistent grapheme to phoneme correspondences favors phonological pathways, whereas reading deep orthographies (e.g. French and English) with inconsistent grapheme to phoneme correspondences favors lexical pathways.

A few neuroimaging studies have brought evidence for a modulation of brain activity by orthographic depth of the used language in word reading.

Using PET imaging, Paulesu et al. (2000) showed that native English readers rely more strongly on left posterior inferior temporal and anterior inferior frontal areas than native Italian readers, associated with lexical processes. By contrast, monolingual Italian readers showed stronger activity than English readers in left superior temporal areas, associated with phonological non-lexical processes. Investigating lexical decision in French–Arabic bilinguals (with Arabic being the relatively deep orthography), Simon, Bernard, Lalonde, and Rebai (2006) showed that the N320, a component associated with spelling-to-sound conversion (Ashby, Sanders, & Kingston, 2009; Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Carreiras, Perea, Vergara, & Pollatsek, 2009; Grainger, Kiyonaga, & Holcomb, 2006; Hauk, Davis, Ford, Pulvermuller, & Marslen-Wilson, 2006; Huang, Itoh, Suwazono, & Nakada, 2004; Proverbio, Vecchi, & Zani, 2004; Simon, Bernard, Largy, Lalonde, & Rebai, 2004; Simon et al., 2006), differentiated French and Arabic words. Similarly, Bar-Kochva and Breznitz (2012) showed larger event-related potential amplitudes to a deep (unpointed) than shallow (pointed) version of Hebrew script 340 ms after word-onset when they were presented to Hebrew bilinguals.

However, several methodological issues of the studies conducted so far on the impact of orthographic depth in word reading limit their interpretability. In studies applying between-subject designs, the observed effects could be related to inter-subject heterogeneity resulting from socio-cultural differences (Paulesu et al., 2000). Other studies used non-matched stimulus lists, e.g. by comparing pointed versus unpointed Hebrew scripts (Bar-Kochva & Breznitz, 2012), which may lead to confounds related to unbalanced familiarity and/or frequency across orthographic depth. Finally, bilingual EEG reading studies on the effect of orthographic depth (Bar-Kochva & Breznitz, 2012; Simon et al., 2006) did not perform analysis in the brain space, limiting conclusions about the brain pathways underlying the effects observed at the scalp.

In a recent study minimizing the confounds related to inter-subject heterogeneity and differences in stimuli lists, we found a modulation of the routine phonological non-lexical pathways engaged in pseudoword reading depending on the orthographic depth of language context (Buetler et al., 2014). The exact same pseudowords were presented to highly equi-proficient French–German bilinguals and the orthographic depth of PW reading was manipulated by embedding them among either a set of French (deep orthography) or German (shallow orthography) words. We showed that pseudoword reading in a shallow context relied more strongly on phonological frontal phonological pathways than reading in the deep orthographic context. In contrast, reading pseudowords in a deep orthographic context recruited less routine phonological pathways, reflected in a stronger engagement of visuo-attentional parietal areas in the deep than shallow orthographic context. These results were interpreted in terms of supporting a modulation of reading route by orthographic depth.

However, the utilization of pseudowords as target stimuli might have enhanced attentional demands and the differences we found might reflect controlled instead of automatic processing. In addition, the use of PWs as target stimuli likely reinforced assembled/phonological reading in both languages and may thus not reflect natural everyday reading, especially in the French context.

In the present study, we aimed at extending the findings on pseudoword reading to a more "natural" setting and to analyze the impact of orthographic depth on reading route selection in (French versus German) word reading. For this purpose, we focused on the EEG responses to the word stimuli presented to reinforce the linguistic context in Buetler et al. (2014), resulting in a French versus German word reading contrast. Investigating reading in highly equi-proficient (French–German) bilingual subjects allowed to minimize potential confounds arising from inter-subject comparisons. Bilingualism is an advantageous model to investigate the neural underpinnings of reading, since there is evidence for a certain degree of independency in word processing for each language context (Kovelman, Baker, & Petitto, 2008; Rodriguez-Fornells, Balaguer, & Munte, 2006; Soares & Grosjean, 1984). In addition, reference-independent electrical neuroimaging analysis and electrical source estimations (e.g. Lehmann, 1987; Tzovara, Murray, Michel, & De Lucia, 2012) were performed on event-related potentials to French and German word reading to investigate if the pathways engaged to map graphemes and phonemes are modulated by the orthographic depth of the language being read.

Reading highly familiar words will probably strengthen lexical processing independent of orthographic depth of the language. However, we predict that compared to the deep orthography, reading in the shallow orthography might rely more strongly on phonological networks. In turn, reading in deep orthography might more strongly recruit lexical pathways than reading in the shallow orthography. Thus, we expect a differential engagement of lexical versus phonological pathways between pre-lexical and semantic processing stages (~300 ms; e.g. Bentin et al., 1999; Grainger et al., 2006) when contrasting French versus German word reading.

2. Material and methods

The present study is based on a new analysis of data obtained by Buetler et al. (2014), in which the procedure and task are already detailed; we thus present only the main methodological parameters here. In contrast to Buetler et al. (2014), where pseudowords were analyzed, the present study contrasts "natural" French versus German word reading.

2.1. Participants

Fourteen female French/German bilinguals participated in the study, aged 18–24 years (mean = 20.86 years, SD = 2.03 years). According to the Edinburgh Inventory, all participants were right-handed (Oldfield, 1971). No participant had a history of reading difficulties, neurological or psychiatric illness and all reported normal or corrected-to-normal vision. The Ethics Committee of the University of Fribourg approved the informed consent procedures.

2.2. Bilingual proficiency

2.2.1. Age of acquisition and immersion

A questionnaire assessed French and German language immersion by asking the participants for the age of acquisition, how long they lived in a region where predominantly German or French was spoken, which language they spoke with their family members, in school, in present activities (watching TV/listening to radio, reading books, mental arithmetic's), and if the language was acquired in school or out of school only.

2.2.2. Expertise

In a self-evaluation part, participants had to indicate in percentages how well they would estimate their reading, speaking, comprehension and writing skills.

2.2.3. Computer-based reading evaluation

Finally, a sub-test from the computer-based DIALANG language diagnosis system was performed to evaluate reading performance (Zhang & Thompson, 2004). Here, participants had to indicate for each of 75 stimuli whether it was a correct word in the corresponding language (French or German) or a highly word-like pseudoword.

From a total of 22 variables tested, three differed significantly between French and German (first language spoken by mother (G > F); language preferred to watch TV/listening to radio (G > F); preferred language to perform mental arithmetic's (F > G)). However, when correcting for multiple comparisons [Bonferroni (Dunn, 1961) or Holm-Bonferroni (Holm, 1979)] to counteract false positive findings (Miller, 1966), none of the variables tested reached significance level (for details, see Buetler et al., 2014).

2.3. Stimuli

Target stimuli of the study were 480 French and 480 German Words,[1] all nouns, composed of 4–6 letters to avoid eye movements. French Words were selected from Lexique database (New, Pallier, Ferrand, & Matos, 2001). Examples of French words include: *Écho*, *Trou*, *Année*, *Femme*, *Aspect* and *Esprit*. German Words were selected from CELEX database (Baayen, Piepenbrock, & Gulikers, 1995). Examples of German words include *Maus*, *Kind*, *Draht*, *Seite*, *Prämie* and *Lösung*.

The word lists were closely matched across languages on length (French mean = 5 letters, German mean = 5 letters; $t(958) = 0.000$, $p = 1.000$), log-transformed lexical frequency (French mean = 1.59, German mean = 1.60; $t(958) = 0.250$, $p = 0.803$; WordGen, Duyck, Desmet, Verbeke, & Brysbaert, 2004), neighborhood size (French mean = 3.31, German mean = 3.31; $t(958) = 0.000$, $p = 1.000$; WordGen, Duyck et al., 2004), summated bigram frequency (French mean = 11328, German mean = 11,447; $t(958) = 0.312$, $p = 0.755$; WordGen, Duyck et al., 2004), length in syllables (French mean = 1.52, German mean = 1.59; $t(958) = 1.856$, $p = 0.064$) and rated word concreteness (French mean = 3.96, German mean = 3.89; $t(933) = 1.120$, $p = 0.263$).

Mean consistency of grapheme–phoneme associations for French words (token-based, i.e., weighted by word frequency) was 83% (2% of words were excluded from the analysis because they were not present in the database; Manulex-infra, Peereman, Lete, & Sprenger-Charolles, 2007). Grapheme–phoneme consistency for German words could not be calculated since to our knowledge, no equivalent measure is available. However, in literature, it is well acknowledged that German is a language with highly consistent grapheme to phoneme associations (e.g. Landerl, Wimmer, & Frith, 1997; Seymour et al., 2003). To illustrate, the grapheme "a" stands for the same phoneme (/a/) in the German words "Land" and "Ball", while the same grapheme represents different phonemes in the corresponding French words "pays" (/e/) and "balle" (/a/). Different pronunciations of the same grapheme such as in the French words "femme" ([fam]) and "ferme" [fɛʀm] or "écho" [eko] and "échec" [eʃɛk] are highly unlikely in German (Phonetic notations are represented according to the International Phonetic Alphabet; International Phonetic Association).

2.4. Procedure and task

The task in this study was to read aloud French and German words displayed on a computer screen. Stimulus delivery and response recording were controlled using E-Prime 2.0 (Psychology Tools, Inc., Pittsburgh, PA).

Participants were seated in an electrically shielded and sound attenuated booth 90 cm in front of a 21-in. LCD screen. Stimuli were presented in black font color on white background in the center of the screen. Each trial started with the presentation of a fixation cross of 400 ms duration, followed by a stimulus displayed for 472 ms and terminated by a response window displaying a fixation cross with a random duration between 1200 and 1700.

The experiment was divided into two language sessions: In the French language session, the stimuli consisted of 480 French words; in the German language session, the stimuli consisted of 480 German words. The French and German language sessions were separated by a pause of at least 10 min. The order of language sessions was randomized across participants. In order to activate the given language, a short text written in the corresponding language was presented at the beginning of each language session. Then, participants could familiarize the procedure in a 2 min training block with words in the language of the selected session, before the experimental phase was initiated. To reduce fatigue, stimuli presentation of one language session was divided into four blocks and the order of blocks randomized across participants.

2.5. EEG acquisition and preprocessing

Electroencephalography (EEG) was recorded with a sampling rate of 1024 Hz with a 128-channel Biosemi ActiveTwo system (Biosemi, Amsterdam, Netherlands) referenced to the CMS-DRL ground. Cartool software (Brunet, Murray, & Michel, 2011) was used to process the EEG data offline. EEG epochs from 100 ms pre-stimulus to 500 ms post-stimulus onset (i.e., 102 data points before and 512 data points after stimulus onset) were extracted from the raw EEG. Event-related potentials (ERPs) were calculated by averaging the extracted epochs for each participant and condition (French and German words) separately. EEG epochs with eye blinks or noise were removed based on a semi-automated artifact

[1] In addition, the same set of 120 pseudowords and 120 symbol strings were presented and pseudo-randomly intermixed with words in both language context sessions (for details, see Buetler et al., 2014).

rejection approach with a ±80 μV criterion at any channel. Data were then band-pass filtered (0.18–40 Hz), notch filtered at 50 Hz and recalculated against the average reference. ERPs at artifacted electrodes from each participant were interpolated using a 3-dimensional spline algorithm before group averaging (Mean 6.25% interpolated electrodes; Perrin, Pernier, Bertrand, Giard, & Echallier, 1987). The average number (±SEM) of accepted epochs was 429 ± 12.49 for French words and 434 ± 9.05 for German words. These values did not differ statistically ($t(13) = 0.386$, $p = 0.706$), minimizing potential differences due to variations in signal-to-noise ratios across conditions.

2.6. Behavioral analysis

Production latencies (reaction times) were assessed with Praat speech analysis software (Boersma & Weenink, 2013) and compared across conditions to determine whether they varied across languages. Due to invalid recordings, only twelve out of fourteen participants were included into behavioral analyses. Trials containing reaction times (RTs) exceeding ±2 standard deviations (SD) from the mean were considered as outliers/errors and excluded from analysis, which resulted in the removal of a total of 3% of trials from French condition (mean number of excluded words = 15) and 3% of trials from German condition (mean number of excluded words = 14).

To investigate whether production latencies differentiate across languages, a paired *t*-test was performed contrasting French words versus German words.

Response accuracy of word production was assessed by auditory inspection of the audio files generated with E-Prime to determine whether they varied across languages. Expected pronunciations were a priori defined by a native German and a native French speaker.

To investigate whether response accuracy rates differentiate across conditions, a paired *t*-test was performed contrasting French words versus German words.

Significance threshold was set at $p < 0.05$. Data analyses were performed using IBM SPSS Statistics 19 (2012).

2.7. Event-related potential analyses

2.7.1. Voltage waveform analyses

Waveform analyses were performed to determine time periods where ERP amplitude differences occurred between French and German word reading.

Time-frame wise paired *t*-tests were computed between the evoked potentials to French word reading vs. German word reading for each electrode.

2.7.2. Global electric field analysis

Global electric field analysis examines qualitative and quantitative measures of the electric field at the scalp. It entails analyses of response strength and response topography to differentiate quantitative effects due to modulation in the strength of responses of statistically indistinguishable brain generators from qualitative alterations in the configuration of these generators (i.e. the topography of the electric field at the scalp; for details see Michel et al., 2004; Murray, Camen, Gonzalez Andino, Bovet, & Clarke, 2006; Murray et al., 2004). These analyses, also known as electrical neuroimaging, have several advantages over canonical waveform analyses. In contrast to canonical waveform analyses, electrical neuroimaging analyses are reference-independent (Lehmann, 1987; Tzovara et al., 2012) and avoid experimenter biases because no pre-selection of time windows and electrode sites that will be submitted to statistical tests is required.

Modulations in the strength of the electric field at the scalp were quantified using global field power (GFP; Koenig & Melie-Garcia, 2010; Lehmann & Skrandies, 1980; Murray, Brunet, & Michel, 2008). GFP is calculated as the standard deviation of the voltages/potentials measured at each electrode and time point. GFP measures the global strength of the response independently of the spatial distribution, i.e. changes in the source configuration. Paired *t*-tests were performed at each time point to statistically analyze changes in GFP between French and German language condition. Correction was made for multiple hypotheses testing by applying an 11 contiguous data-point temporal criterion for the persistence of significant differential effects (Guthrie & Buchwald, 1991).

Topographic modulations were identified using global map dissimilarity (GMD; Lehmann & Skrandies, 1980). GMD is calculated as the root mean square of the difference between two strength-normalized vectors (here the instantaneous voltage potentials across the electrode montage, i.e. "maps"). GMD quantifies topographic differences between two electric fields, independent of pure amplitude modulations across conditions. Since topographic changes necessarily follow from differences in the configuration of the brain's underlying active generators (Lehmann, 1987; Srebro, 1996), this analysis provides a statistical means to determine if and when brain networks mediate responses to French and German word reading. GMD values between French and German language condition were compared at each time point with an empirical distribution derived from a Monte Carlo bootstrapping analysis procedure (5000 permutations per data point) based on randomly reassigning the data of each participant to either the French or German condition (topographic ANOVA or "TANOVA", detailed in Murray et al., 2008). Correction was made for temporal auto-correlation by applying a >11 contiguous data-point temporal criterion for the persistence of significant differential effects (Guthrie & Buchwald, 1991).

2.7.3. Electrical source estimations

A distributed linear inverse solution and the local autoregressive average (LAURA) regularization approach were used to estimate intracranial sources of the scalp-recorded data (Grave de Peralta, Gonzalez, Lantz, Michel, & Landis, 2001; Grave de Peralta, Murray, Michel, Martuzzi, & Gonzalez Andino, 2004). Intracranial sources were estimated and statistically processed over the periods showing a topographic and/or a GFP modulation. ERPs for each participant and condition (French and German words) were first averaged over the period of interest. Then, intracranial sources were estimated for the resulting one time-sample ERP for each participant and condition. The sources were then statistically compared at each solution point between the experimental conditions using paired *t*-tests. The solution space included 3005 nodes, selected from a 6 × 6 × 6 mm grid equally distributed within the gray matter of the averaged brain of the Montreal Neurological Institute (MNI; courtesy of Grave de Peralta Menendez and Gonzalez Andino, University Hospital of Geneva, Geneva, Switzerland). In order to control for multiple comparisons, only solutions with a minimal cluster size of 15 consecutive points (k_E) were retained (see also De Lucia, Clarke, & Murray, 2010; Knebel & Murray, 2012).

Significance threshold for all analyses was set at $p < 0.05$. Analyses on event-related potentials were carried out using Cartool software (Brunet et al., 2011).

3. Results

3.1. Behavioral results

Mean RTs (SD) on the whole group of 12 subjects were for French words 720 ms (168 ms) and German Words 706 ms

(165 ms). Paired *t*-test showed a significant difference between French and German words ($t(11) = 2.72$, $p = 0.02$; $\eta_p^2 = 0.402$).

Mean accuracy (SD) on the whole group of 12 subjects were for French words 98% (7%) and German words 98.5% (8%). Paired *t*-test showed no significant difference between French and German words ($t(11) = 0.562$, $p = 0.585$; $\eta_p^2 = 0.028$).

3.2. Event-related potential analysis

3.2.1. Voltage waveform analyses

Evoked potential waveforms to the words presented in the two languages are depicted in Fig. 2 for 7 exemplar electrodes and in Fig. 1A for all 128 electrodes.

Paired *t*-tests between the ERP to French versus German words revealed an increase in the number of electrodes showing a statistically significant difference over the time interval of 240–314 ms post-stimulus onset ($p < 0.05$, >1 ms, Fig. 1B).

3.2.2. Global electric field analysis

Global field power analysis identified significant differences between French and German language condition 262–314 ms post-stimulus onset ($p < 0.05$; min. duration threshold = 11 contiguous time frames; German > French; Fig. 1C).

Global map dissimilarity analysis identified a significant topographic modulation between French and German language conditions 240–278 ms post-stimulus onset ($p < 0.05$; min. duration threshold = 11 contiguous time frames; Fig. 1D).

3.2.3. Electrical source estimations

In order to localize the effect in the brain space, paired *t*-test of LAURA distributed source estimations between French and German words were performed for each of the 3005 solution points for time-averaged ERPs over the period of interest defined by the global electric field analysis of topographic and/or GFP modulation. This analysis revealed a significant difference of activation within left insular, posterior cingular, inferior frontal, dorsolateral and anterior prefrontal regions (German > French; $p < 0.05$; $k_E = 15$; Fig. 1E).

4. Discussion

We investigated the spatio-temporal impact of orthographic depth on overt word reading. Matched French and German words were presented to highly equi-proficient bilinguals. Our results show that reading words in languages with different orthographic depth indices impacts brain response to word reading. Electrical neuroimaging analyses of event-related potentials to German and French word reading revealed a difference in response strength (German > French) with a concomitant topographic modulation 240–314 ms post-stimulus onset, indicative of distinct brain networks engaged in reading during this time-window. Analysis of electrical source estimation over the period of topographic modulation showed a differential engagement within left insular, posterior cingular, inferior frontal, dorsolateral and anterior prefrontal regions.

The topography of the ERPs to words differed 240–278 ms post-stimulus onset when they were read in languages with different orthographic depths. Because distinct topographies necessarily follow from distinct configuration of the underlying brain network (e.g. Lehmann & Skrandies, 1980), our result indicates that the language of word reading modulated the brain networks involved in reading. The timing of the topographic modulation corresponds to the latency that has previously been associated to processing stages involved in grapheme to phoneme mapping (Ashby et al., 2009; Bentin et al., 1999; Carreiras et al., 2009; Grainger et al., 2006; Hauk et al., 2006; Huang et al., 2004; Proverbio et al., 2004; Simon et al., 2004, 2006), occurring between letter identification (Appelbaum, Liotti, Perez, Fox, & Woldorff, 2009; Brem et al., 2006; Lin et al., 2011; Martin, Nazir, Thierry, Paulignan, & Demonet, 2006; Maurer, Brandeis, & McCandliss, 2005) and semantic processing (Bentin et al., 1999; Simon et al., 2006). Since the words were matched in terms of lexical characteristics (length, frequency and neighborhood size) and only differed in terms of grapheme-to-phoneme consistency, the topographic difference most likely reflects distinct networks recruited to map graphemes and phonemes across languages.

According to the Dual Route Cascade Model, graphemes and phonemes may be mapped on a lexical or a phonological (non-lexical) route (Coltheart et al., 2001). The phonological route is independent of lexico-semantic representations and each grapheme is sequentially mapped to its corresponding phoneme. The phonological route is thus preferentially recruited in regular word, non- and pseudoword reading (e.g. Jobard et al., 2003). In contrast, words, especially irregular words, may be more efficiently processed on the lexical route, which accesses orthographic and phonological lexical memory structures to retrieve phonemes (e.g. Jobard et al., 2003).

Since in the present study the lexicality of stimuli was matched across languages, the regularity of words might have crucially mediated the brain networks engaged, especially the regularity between languages, i.e. the orthographic depth. The orthographic depth refers to the degree of consistency of grapheme/phoneme correspondences and varies across languages from high in shallow orthographies to low in deep orthographies. Originally postulated by Katz and Feldman (1983; revised by Katz & Frost, 1992), the Orthographic Depth Hypothesis assumes that in transparent orthographies, phonological pathways are preferentially recruited to map graphemes and phonemes. In contrast, the sequential mapping via phonological pathways may be insufficient to map grapheme and phoneme in languages with irregular orthographies. Instead, irregular languages may favor lexical pathways where phonemes are retrieved from memory structures.

Thus, the topographic modulation at 260 ms after word onset reflects, in our model, distinct pathways engaged to map graphemes and phonemes due to the differences in the orthographic regularity of the two languages.

The statistical analyses of electrical source estimations over the period of topographic modulation support the hypothesis of an orthographic-related reading route modulation by showing a stronger engagement of left insular, inferior frontal and dorsolateral prefrontal regions when reading German than French words.

The differential engagement of this network suggests that reading German words relied more strongly on phonological pathways than reading French words. Indeed, these areas have previously been linked to grapho-phonological processing. More specifically, the left insula has been discussed to be part of the phonological loop and phonological working memory (Chee, Soon, Lee, & Pallier, 2004; Schulze, Zysset, Mueller, Friederici, & Koelsch, 2011). Left inferior frontal regions have been linked to phonological processing (Price, 2000), especially grapheme to phoneme conversion (Fiebach et al., 2002; Heim et al., 2005; Rodriguez-Fornells et al., 2006; Wheat et al., 2010) and enhanced short term memory capacities of phonological pathways compared to lexical pathways (Jobard et al., 2003; Nixon et al., 2004). Finally, left dorsolateral prefrontal regions were linked to phonological working memory and sublexical conversion (Pecini et al., 2008). Thus, these findings are in line with our hypothesis, assuming a modulation of reading route due to the different orthographic depth of languages and a stronger engagement of phonological non-lexical pathways in German than French word reading.

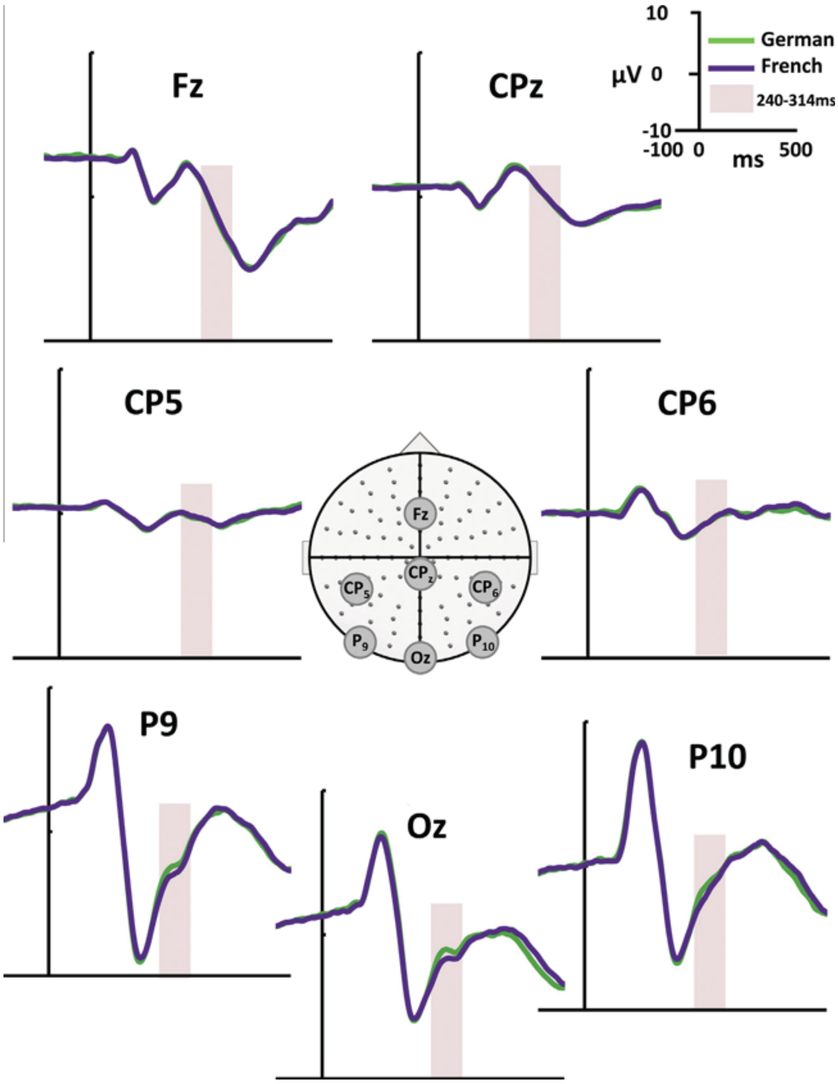

Fig. 1. Exemplar ERP waveforms. Exemplar group-averaged ERP waveforms (Fz, CPz, Cp5, CP6, P9, P10, Oz) to French (purple) and German (green) word reading are plotted in microvolts as a function of time. In the middle of the figure, the array of the 128 electrodes with the electrode position of the displayed waveforms is presented.

A higher engagement of posterior cingular regions was found in German than French word reading. This finding further supports our conclusion on a stronger engagement of phonological pathways in shallow versus deep orthography, since the activation of the posterior cingulate cortex has been associated to the detection and reliance on phonological and orthographic consistency (Bolger, Hornickel, Cone, Burman, & Booth, 2008). This region has also been discussed to subserve lexical processing as it has shown greater activity in decoding words than pseudowords (Ischebeck et al., 2004) and non-words (Binder et al., 2005). However, in word versus non- or pseudo-word contrasts, effects of lexicality may be confounded with effects related to phonological and orthographic consistency, i.e. the posterior cingular engagement found in these studies might reflect higher orthographic consistency of words compared to pseudo-/non-words instead of higher lexicality. Together with the broad phonological network found to show enhanced activity in German compared to French word reading, we interpret this finding as to reflect a stronger engagement of phonological networks when reading an orthographically shallow than deep language (Fig. 3).

In addition to the differential activation of insular and frontal phonological areas, a stronger activation of left anterior prefrontal regions was found for German than French word reading. The anterior prefrontal cortex has been linked to various higher cognitive processes such as executive functions (for a review see Ramnani & Owen, 2004), but to our knowledge, its role in reading processing is currently unknown. One explanation for the increase in activity of anterior prefrontal regions in German compared to French might be that it reflects enhanced cognitive control due to local phonological feature analysis in shallow word reading versus global lexical analysis in deep word reading. However, further research is needed to clarify the role of anterior prefrontal regions in phonological processing.

Contrary to our predictions, no enhanced activation was found in structures usually linked to lexical processing in French compared to German word reading. According to the Orthographic Depth Hypothesis (Katz & Feldman, 1983), reading an orthographically irregular language (French) should rely more strongly on lexical pathways than reading an orthographically regular language (German). The Dual Route Cascade Model, on the other hand, posits the engagement of lexical pathways in familiar word reading (Coltheart et al., 2001). Our results suggest that the Orthographic Depth Hypothesis and the Dual Route Cascade Model should be integrated. Familiar word reading might recruit lexical pathways independent of the orthographic depth of a language. Thus, in the present word versus word contrast, no modulation of lexical

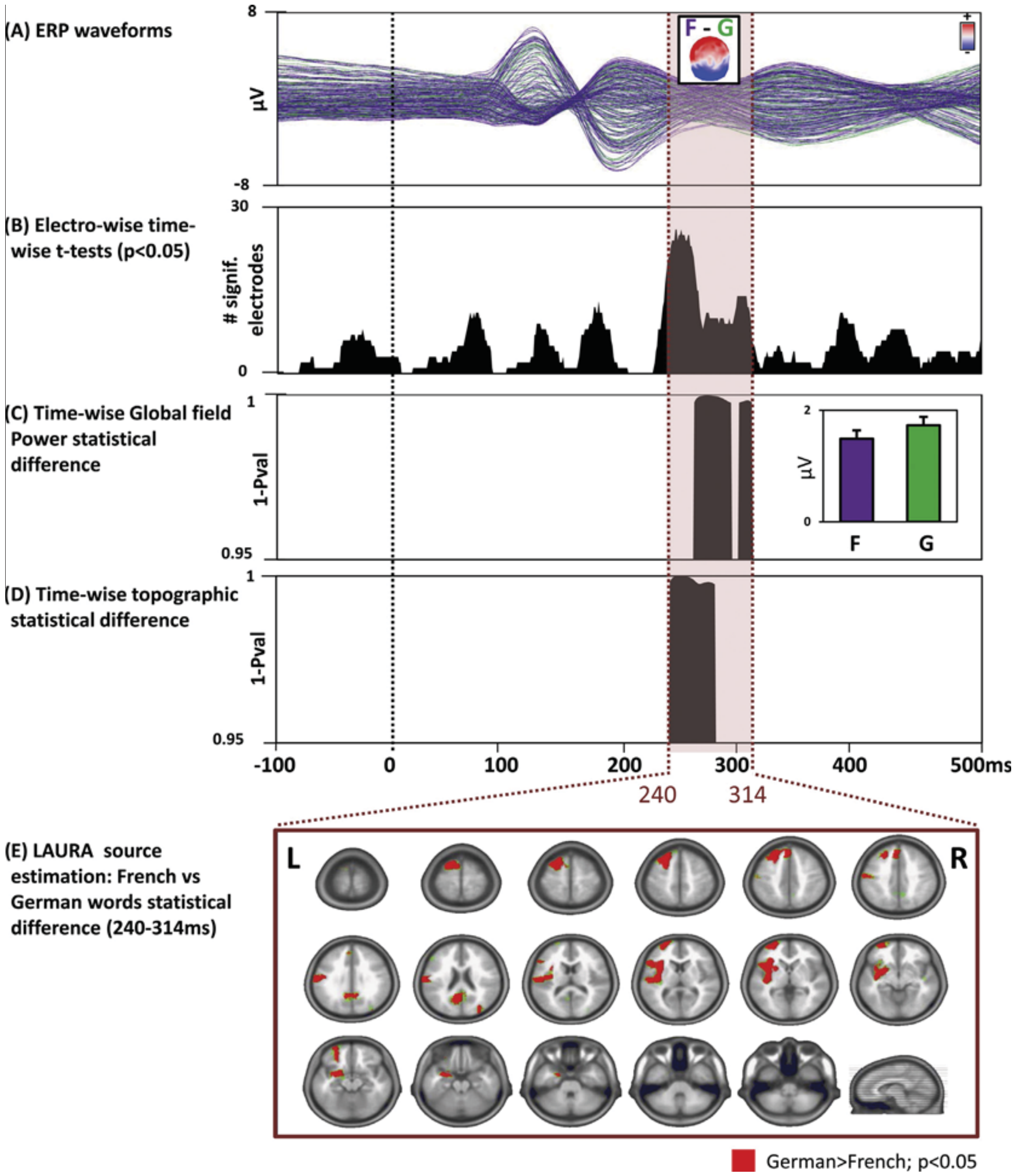

Fig. 2. Electrical neuroimaging results. (A) ERPs waveform. The group-averaged ERPs to French (purple) and German (green) word reading are displayed in microvolts as a function of time relative to stimulus onset (dotted black line). The time period showing significant topographic differences between the conditions is indicated in red ($p < 0.05$). The French–German scalp topography difference map over the 240–314 ms period after stimulus onset is represented nasion upward and left scalp leftward. (B) Time-wise electrode-wise *t*-tests. Results of the time-wise paired *t*-tests at each of the 128 scalp electrodes from the group-averaged ERP waveforms are shown ($p < 0.05$). (C) GFP analyses. Results of the time-wise paired *t*-tests on the global field power contrasting French versus German word reading are displayed as $1 - p$ value (*y*-axis) as a function of time (*x*-axis). Only periods showing significant differences in GFP are displayed (German > French; $p < 0.05$; 11 contiguous time frame temporal criterion). In the black box, the response strength for the 240–314 ms period is represented for French (F) and German (G) condition in microvolts (+SEM). (D) GMD analyses. Results of the time-wise analysis of the global map dissimilarity (TANOVA) contrasting French versus German word reading are displayed as $1 - p$ value (*y*-axis) as a function of time (*x*-axis). Only periods showing significant topographic differences are displayed ($p < 0.05$; 11 time-frame temporal criterion). (E) Distributed LAURA source estimations. Results of Paired *t*-tests were performed for each of the 3005 solution points for time-averaged ERPs over the period of topographic modulation (240–314 ms after stimulus onset) revealing differential activation of left insular, posterior cingular, inferior frontal, dorsolateral and anterior prefrontal regions (German > French; $p < 0.05$; $k_E = 15$) when reading French versus German words.

pathways would be expected. However, these routine lexical pathways in word reading may be more strongly reinforced by phonological pathways in the shallow than deep orthography. Efficient processing of regular words may involve both, global lexical and local phonological pathways, however, irregular words may not successfully be processed with a local strategy and thus mainly depend on global lexical pathways.

The conclusion on a stronger reinforcement of routine lexical word processing by phonological pathways in shallow but not deep orthography is supported by analyses of global field power and behavioral data. The global field power differed across languages 262–314 ms after stimulus-onset. During this time-window, reading German words was associated to higher response strength than reading French words. Source estimations revealed that the difference in GFP was due to a modulation of the activity in the same left-lateralized networks which showed a differential engagement over the period of topographic modulation (posterior cingular, insular, inferior frontal, dorsolateral and anterior pre-

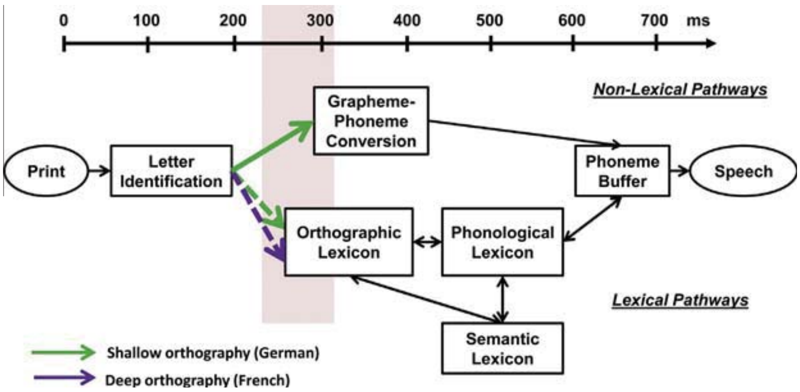

Fig. 3. Integration of the Dual Route Cascade Model and Orthographic Depth Hypothesis. According to the Orthographic Depth Hypothesis (Katz & Feldman, 1983), reading an orthographically irregular language should rely more strongly on lexical pathways than reading an orthographically regular language. The Dual Route Cascade Model, on the other hand, posits the engagement of lexical pathways in familiar word reading (Coltheart et al., 2001). Our results suggest that the Orthographic Depth Hypothesis and the Dual Route Cascade Model should be integrated. Reading highly familiar words may recruit routine lexical pathways (dotted arrows) in shallow (green) and deep orthography (purple), thus being canceled in the present study design. However, the routine lexical pathways engaged in word reading may be enhanced by non-lexical networks (plain green arrow) in the shallow but not deep orthography, reflected in a stronger engagement of insular-frontal phonological areas in German versus French word reading.

frontal regions). Thus, the higher response strength in German than French word reading might reflect that a larger network including the regions involved in both lexical and phonological processing was engaged in German, whereas predominantly the lexical route was engaged when reading in the French context. Furthermore, the shorter RTs found in German than French word reading (with comparable accuracy across languages) might result from faster word processing due to enhanced network activity in shallow than deep word reading.

In bilinguals, the engagement of lexical pathways across languages in word reading is of particular interest, since two languages must be lexico-semantically represented in the brain. Whereas early models on bilingual reading processing assume separated lexica for L1 and L2, recent empirical data such as cross-language competition and language switching costs support the notion of a common lexical representation of different languages. The most prominent model assuming non-selective lexical access in bilinguals is the Bilingual Interactive Activation Model (BIA), and its updated version, the BIA + model. According to the BIA + model, the different languages of a bilingual subject are simultaneously activated and interconnected via common nodes. More precisely, a letter string activates via nodes all words in the lexicon containing the given letter on the same position independent of languages. The more a word corresponds to the pattern of letters of the original input, the more nodes are activated. Simultaneously, words with low or non-matching letter patterns receive less or no activation when not matching the original input on one or multiple positions. Consequently, words which fully match the original input pattern are most activated, which is – except for cognates – usually the case for one word in one language. In cognates (i.e. orthographically similar/identical words across languages (e.g. “flamme” (French), “Flamme” (German), “flame” (English)), language context information might crucially impact phonological coding by emphasizing distinct brain networks associated with lexical entries in either L1 or L2. Thus, depending on the preceding stimulus, grapheme–phoneme mapping rule selection in L1 or L2 will be facilitated. Language context may pre-activate specific brain networks and thus facilitate grapheme–phoneme associations for the corresponding language, restricting non-selective access of word recognition. Moreover, repeated exposure to a language may lead to adaptations of the reading network to the specific linguistic demands of a language. Thus, language context may minimize L1 and L2 competition by emphasizing specific brain networks associated with either L1 or L2 conversion rules shaped via learning-induced network weighting.

Together, the spatio-temporal neuroimaging data and behavioral results support the Orthographic Depth Hypothesis by showing that word reading in a language with consistent grapheme/phoneme correspondences (German) was associated to a stronger engagement of phonological pathways than reading in a language with inconsistent grapheme/phoneme correspondences (French). However, the absence of a modulation of lexical pathways suggests that they may be equally engaged in familiar word reading across languages. Thus, the routine lexical pathways engaged in word reading may be reinforced more strongly by phonological networks in the shallow than deep orthography.

The present study extends previous findings obtained in PW reading by our group, where we showed a modulation of routine non-lexical pathways depending on whether the PWs were read in a French or German language context (i.e. PWs were pseudo-randomly intermixed with French or German words; Buetler et al., 2014). The results of the present study suggest that the effect of orthographic depth on reading routes found in PW reading may be generalized to natural word reading. Compared to the French versus German PW reading contrast, where effects showed up ∼330 ms after stimulus onset, the effects found in French versus German word reading occurred earlier in time, namely around 260 ms post-stimulus onset. The relative early latency of the effect of orthographic depth found in word reading could be due to the fact that regular word processing predominantly engages faster lexical pathways, whereas PW reading is more strongly supported by less efficient non-lexical pathways. In line with this conclusion, reading aloud literature has suggested a broad time window ranging from 150–330 ms to be engaged in grapheme to phoneme mapping, depending on task and stimuli used. Consistently, both studies show that German word and PW reading seem to rely more strongly on non-lexical networks than their French counterparts. The differential engagement of non-lexical networks in favor of German language was more pronounced when contrasting French and German words than French and German PW reading. PW reading in the German context relied more strongly on left inferior frontal phonological regions compared to PW reading in the French context. German word reading, however, engaged an extensive phonological network within left insular, inferior frontal and dorsolateral prefrontal regions compared to French word reading. This difference in distribution of non-lexical network activation favoring the shallow language may result from the fact that PW reading generally favors non-lexical networks, independent of language context, canceling potential common non-lexical regions in the analysis. In contrast, regular word reading may rely preferably on lexical pathways independent of the language used, thus, non-lexical regions are unlikely to be canceled when contrasted to each other. Interestingly, left inferior frontal phonological regions were consistently found in both studies to support German more strongly than French reading. The fact that phonological inferior frontal regions were more strongly activated in both, German word and PW reading compared to French word or PW reading, suggests that this region might be crucially mediated by the orthographic depth of a language.

Our results must be interpreted within the scope of several limiting factors. First, a balanced proficiency across languages is crucial for the interpretation of our results. Behavioral analysis showed faster RT for German than French word reading, suggesting more proficient German than French reading. Though statistically comparable, marginal confounds related to differences in proficiency could be argued with the fact that for uncorrected *p*-values, 3 out of 22 variables tested differed across languages. However, we consider these differences to have unlikely impacted on reading performance, since the three differentiating variables were linked to oral language production and not reading skills. Variables directly linked to written language skills (reading books, school, computer-based reading evaluation) showed no differences across languages. In addition, the differences did not show the same direction in favor of one language.

A further potential alternative explanation for the difference in RT found across languages could be an unbalanced level of word familiarity. Familiarity effects have been found in reading tasks: increased word familiarity was associated with faster reading performance. Familiarity is difficult to control since this would imply an individual set of stimuli for each participant and language, which, in turn, might introduce additional confounds. However, we consider that familiarity effects were minimized in the present design since (i) no dominant language profile can be defined according to the language variables we tested; (ii) high-frequency words were used; (iii) the individual familiarity distribution of words across languages should vary across participants and thus not lead to persistent confounds in the data analysis; and (iv) despite the geographic location of the present study where French is more frequently used, German word reading was associated to shorter RTs than French word reading.

In addition, differences in RTs could result from potential differences in age of acquisition (AoA) and rated word imageability across languages. Word AoA corresponds to the age at which words were learned. AoA effects were notably reported in reading tasks, with words acquired early in life being processed faster and more accurately than those acquired later. Similarly, increased imageability, a semantic variable indicating how easy it is for a word to arouse mental images, has been reported to be associated with faster word recognition. However, measures of imageability have been reported to be highly positively correlated with measures of concreteness (which were matched in the present study).

Measures for rated AoA and imageability could not be calculated for the present set of stimuli, because only 20% resp. 8% of French words were present in the largest database of reliable norms currently available for word AoA and imageability.

Further, since the stimuli were matched for length in letters across languages, the mean number of syllables per word was higher in German than French due to linguistic differences between the two languages ($p = 0.06$). However, this difference seemed not to have impacted reading performance, since RTs were shorter for German than French words.

In addition, confounds related to physical differences in stimuli could have been caused by the slightly different alphabets used in French and German. However, differences related to physical form of stimuli/letter identification have been linked to earlier time windows (<200 ms; Appelbaum et al., 2009; Brem et al., 2006; Lin et al., 2011; Martin et al., 2006; Maurer et al., 2005).

Finally, in the present design, the words were pseudo-randomly intermixed with PWs (which were target stimuli and analyzed in our previous work; Buetler et al., 2014), potentially enhancing task difficulty introducing controlled instead of automatic processing. However, RTs suggest that the co-presentation of PWs and words generated no extra load when performing the reading task, since they correspond to RTs usually obtained in "pure" word reading tasks. In addition, an oddball design was used, with the vast majority of stimuli being real words (four times more words than PWs). It has been shown that in oddball paradigms, subjects adopt the strategy of the majority, i.e. words. Furthermore, since PWs were intermixed with words across both languages, possible confounds related to controlled processing should be canceled in the analysis. Yet, the presence of PWs might have affected differently German versus French word reading. The routine non-lexical networks favored in PW reading might be more congruent with the majority in the German than French language context. Thus, the faster RT found in German might result from the higher degree of congruency when reading German words along with PWs than reading French words along with PWs. However, this alternative interpretation of our behavioral results would still be in line with our main hypothesis, i.e. the stronger engagement of non-lexical networks in German than French word reading. Yet, our neuroimaging results support our primary conclusion, i.e. the stronger reinforcement of routine lexical word processing by non-lexical pathways in shallow than deep orthography, likely shortening processing speed in German compared to French word reading.

5. Conclusion

The present study provides evidence for a modulation of brain networks engaged in reading by the orthographic depth of a language. Our findings extend current literature on reading processing by showing that in familiar word reading, the routine lexical pathways may be more strongly reinforced by non-lexical networks in the shallow than deep orthography.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandl.2015.10.001.

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