Posterior N1 asymmetry to English and Welsh words in Early and Late English-Welsh bilinguals

Giordana Grossi[1], Nicola Savill[2], Enlli Thomas[2], Guillaume Thierry[2]

[1]State University of New York at New Paltz, [2]Bangor University

Address and correspondence

Giordana Grossi

Department of Psychology, SUNY New Paltz

600 Hawk Drive, New Paltz, NY 12561

ph: (845) 257-2674

fax: (845) 257-3474

email: grossig@newpaltz.edu

Acknowledgements: Many thanks to those who participated in this study, and to Marie Lallier for her invaluable comments on an earlier version of the manuscript. This research was supported by funding from SUNY New Paltz and the ESRC Centre for Research on Bilingualism, Bangor University.

Abstract

We investigated the lateralization of the posterior event-related potential (ERP) component N1 (120-170 ms) to written words in two groups of bilinguals. Fourteen Early English-Welsh bilinguals and 14 late learners of Welsh performed a semantic categorization task on separate blocks of English and Welsh words. In both groups, the N1 was strongly lateralized over the left posterior sites for both languages. A robust correlation was found between N1 asymmetry for English and N1 asymmetry for Welsh words in both groups. Furthermore, in Late Bilinguals, the N1 asymmetry for Welsh words increased with years of experience in Welsh. These data suggest that, in Late Bilinguals, the lateralization of neural circuits involved in written word recognition for the second language is associated to the organization for the first language, and that increased experience with the second language is associated to a larger functional cerebral asymmetry in favor of the left hemisphere.

One of the Event-Related Potential (ERP) components elicited by the presentation of letter strings is the N1, a negative component peaking between 140 and 200 ms over the posterior recording sites (e.g., Bentin, Muochetant-Rostaing, Giard, Echallier, & Pernier, 1999; Cohen, et al., 2000; Maurer, Brandeis, & McCandliss, 2005; McCandliss, Posner, & Givón, 1997; Wydell, Vuorinen, Helenius, & Salmelin, 2003). N1 is part of a family of posterior components hypothesized to reflect mechanisms involved in the rapid categorization of visual stimuli. Indeed, the N1 is elicited by other visual stimuli such as faces and objects (Bentin, Allison, Puce, Perez, & McCarthy, 1996; Rossion, Joyce, Cottrell, & Tarr, 2003; Tanaka & Curran, 2001), but these N1 components usually differ from the N1 to letter strings in terms of timing and scalp distribution.

Studies employing linguistic stimuli have found that the N1 amplitude is modulated by orthographic and lexical factors. For example, in single-word presentation studies, N1 amplitude has been found to be larger to consonant strings than words (Compton, Grossenbacher, Posner, & Tucker, 1991; McCandliss et al., 1997) and larger to low than high frequency words (Hauk & Pulvermüller, 2004; Neville, Mills, & Lawson, 1992; Sereno, Brewer, & O'Donnell, 2003; Sereno, Rayner, & Posner, 1998; but see Proverbio, Zani, & Adorni, 2008). Frequency effects in the N1 time window have been also observed with magnetoencephalography (MEG; e.g., Assadollahi & Pulvermuller, 2003). The direction of these effects is not consistent across studies (Grossi & Coch, 2005; Maurer & McCandliss, 2007), however. For instance, N1 was larger to consonant strings than words in studies by Compton et al. (1991) and McCandliss et al. (1997), whereas it was larger to words (e.g., taxi) than their pseudohomophone letteraltered (e.g., taksi) or case-altered forms (e.g., taXi) in a study by Sauseng, Bergmann, and Wimmer (2004). In a study comparing English orthography with symbols and forms, Bentin et al. (1999) found that the temporo-occipital N170 was larger to words, pseudowords, and nonwords than nonalphabetic (symbols and forms) stimuli in a size judgment task. Furthermore, in a divided visual field study, the temporo-occipital negativity peaking around 200 ms was found to be larger for words than consonant strings (Cohen, et al., 2000). Therefore, although this research clearly suggests that N1 is the earliest ERP component reflecting word categorization and orthographic/lexical processes, the nature of the precise mechanisms at work, and how these mechanisms influence the N1 amplitude, remains unclear.

The N1 has been found to be larger over the left than the right posterior sites in a variety of studies and tasks including lexical decision (Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Simon, Petit, Bernard, & Rebaï, 2007), letter detection (Proverbio, Dal Zotto, & Zani, 2005), semantic categorization (Kim & Kim, 2006; Kim, Yoon, & Wook, 2004), one-back repetition (Maurer et al., 2005), phoneme identification (Proverbio, Vecchi, & Zani, 2004), orientation judgment (Rossion et al., 2003), and orthographic, phonological, and semantic judgment tasks (Spironelli & Angrilli, 2007). Some of the above-mentioned lexical and frequency effects have also been found to be lateralized. For example, the difference in N1 amplitude between words and symbols described by Maurer et al. (2005) was observed only over the left posterior sites (see also Brem, et al., 2009, who employed the same paradigm). Similarly, in Cohen et al. (2000), the difference in N200 amplitude between words and consonant strings was observed only over left temporal and occipital sites.In the same vein, using MEG, Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin (1999) showed a more robust activation of temporo-occipital areas with words than symbols.

The nature of this asymmetry has not been clarified yet. Some authors have linked it to the left hemisphere specialization for word recognition processes. For example, Maurer and McCandliss (2007) proposed that reading circuits become left-lateralized by piggybacking on the neural circuits dedicated to phonological and auditory processing already in place in the left hemisphere (phonological mapping hypothesis, McCandliss & Noble, 2003). According to this hypothesis, the N1 lateralization is related to phonological decoding, or grapheme-to-phoneme conversion, mechanisms (Maurer & McCandliss, 2007). Other authors have also associated the negative temporo-occipital components elicited by alphabetic stimuli between 140 and 200 ms to specialized left hemisphere circuits for print, such as the visual word form area (e.g., Brem et al., 2006; Cohen et al., 2000). The few studies on non-alphabetic languages have provided contradicting results. Kim et al. (2004) and Kim and Kim (2006) found a lateralized N1 for English and Korean but not for Chinese characters in Korean speakers. This result would be expected based on the phonological mapping hypotheses (Maurer & McCandliss, 2007) given that Chinese characters are not processed in terms of grapheme-to-phoneme correspondences, whereas English and Korean are. However, a recent paper by Maurer and colleagues found a similarly left-lateralized N1 for all three Japanese scripts (Hiragana, Katakana, and Kanji) in native Japanese speakers (Maurer, Zevlin, & McCandliss, 2008). Kanji is a logographic language, where characters are directly mapped onto meaning and sounds. Because of this result and because the N1 was left-lateralized for Katakana pseudowords, Maurer et al. (2008) suggested that the left hemisphere specialization, as indexed by N1, reflects familiarity with a language word form. Interestingly, and of significant importance to the present study, the Japanese participants also showed a left-lateralized N1 to familiar English words learned later in life.

N1 asymmetry in children and bilinguals

Recent ERP experiments have shown that the N1 asymmetry is not present in young children. Maurer, Brem, Bucher, & McCandliss (2005) found a left-lateralized N1 for words in adults but not in pre-literate 6;5-year-old children. Spironelli and Angrilli (2009) found a left-lateralized N1 to words in young and middle-age adults, but, on the contrary, the component peaked later and was right-lateralized in 10-year-old children. Interestingly, the N1 asymmetry correlated with age, level of education, and RT (the older, the more educated, and the faster the participants, the more left-lateralized the N1). Although it is possible that the correlations between N1 asymmetry and education and N1 asymmetry and RT be explained by age, Spironelli and Angrilli's data (2009) suggest that the N1 lateralization in monolinguals becomes more robust with age and experience with reading.

The developmental time-course of N1 lateralization raises the interesting question of whether this temporal pattern is also present for individuals who learned a second language late in life. In late bilinguals, not only are the systems involved in spoken language hypothesized to already be in place, but also the system involved in reading. Does word recognition in the second language (L2) piggyback on the neural circuits supporting word recognition in the first language (L1) systems? Is the degree of N1 asymmetry for L1 associated with the degree of N1 asymmetry for L2?

The literature on these issues is sparse. To our knowledge, the first attempt to investigate the effects of L2 learning on changes in N1 amplitude was the study by McCandliss et al. (1997). The authors engaged participants in learning Keki, a miniature artificial language with some orthographic features of English and some non-English-like orthographic patterns. Participants were tested with no training, after 20 hours, and after 50 hours of training. Improvements in stimulus recognition were observed for stimuli with which participants were familiar (English and Keki words) after 50 hours of lab training, but not for novel Keki words. No changes in N1 (170-230 ms) amplitude were found after 50 hours of practice with the new language; N1 remained larger for English than Keki words (the N1 to Keki words was, in turn, larger than the N1 to consonant strings). In contrast, experience influenced the amplitude of a later posterior component, P200, but only for familiar Keki words and not for Keki stimuli that were unfamiliar. According to McCandliss et al. (1997), these data suggest that the P2 modulation and the more efficient recognition of L2 stimuli with training mainly reflected item-specific learning and not the internalization of a new word form system; furthermore, these data suggested that, late in life, the visual system might be incapable of extracting these visual regularities even after prolonged exposure to L2.

Other studies have focused on the comparison between different languages in different groups of bilinguals. As previously mentioned, different patterns of N1 lateralization have been found for different languages within the same participants in late learners (Kim & Kim, 2004; Kim et al., 2006). In a study employing a sentence congruency task, Proverbio, Čok and Zani (2002) found that early compound[1] Italian-Slovenian bilinguals showed an N1 to the last word that was larger over the left than right posterior sites for Slovenian but not for Italian, who had a bilateral N1. On the contrary, a left-lateralized N1 was present for Italian monolinguals. This pattern suggests that other factors might play a role in N1 asymmetry besides training and familiarity, given that Proverbio et al.'s participants were extremely familiar with both languages. In a more recent study, Maurer et al. (2008) found that the N1 to English words was left-lateralized in Japanese speakers familiar with English (L2). These participants started to learn English around 10 years of age and had been living in an English speaking country for almost 10 years. Therefore, they showed the same degree of lateralization for L1 and L2.

These studies (Kim & Kim, 2004; Kim et al., 2006; Maurer et al., 2008; Proverbio et al., 2002) differ on a number of factors: age of acquisition and length of experience with L2, social environment, tasks, and specific languages spoken. It is therefore difficult to draw any conclusions on the lateralization of N1 in bilingual participants. In the present study, early and late English-Welsh bilinguals were tested on the same semantic categorization task. In terms of orthography-to-phonology mapping, Welsh is more a transparent language, whereas English is an opaque language (Ellis & Hooper, 2001). We anticipated that the comparison between these two languages would provide useful information regarding the nature of the N1 lateralization.

The present study

[1] Proverbio et al. (2002) defined ‘‘early compound’’ bilinguals based on Genesee, Hamers, Lambert, Mononen, Seitz, and Stark (1978) as "…. bilinguals as they grew up in bilingual families and acquired both languages before the age of 5 in the same social–emotional context." (p. 1008-1009).

The data presented here are part of a large study aimed at investigating cross-language interactions in early and late bilinguals as indexed by neighborhood density (ND) effects. ND is defined as the number of words that differ from a given word by a single letter (Coltheart, Davelaar, Jonasson, & Besner, 1977). Here, we focus on N1 lateralization for the two languages. Early Bilinguals learned to read and write in both languages before the age of 5, whereas Late Bilinguals learned Welsh at or after puberty. Participants were presented with single words and instructed to press a button every time an animal name would appear on the screen. They were presented with four blocks of trials, two for each language, with each block repeated twice. To avoid confounding effects due to the repetition of the stimuli, we present the data from the first blocks only.

If N1 asymmetry develops slowly and after a prolonged experience with a second language (as it develops slowly for the first language in children; e.g., Maurer et al., 2005; Spironelli & Angrilli, 2009), then N1 asymmetry should be correlated with measures of experience with, and/or competence in, the L2 in Late Bilinguals. If this development is somehow linked to the neural organization for L1, we would expect to see a correlation between N1 asymmetry for Welsh and N1 asymmetry for English. The comparison between Early and Late Bilinguals would allow us to assess whether qualitative differences exist between learning to read in two different languages as a child and learning to read in a second language late in life.

Finally, we note that Spironelli & Angrilli (2009) found that N1 asymmetry correlated with age, education level, and RTs in an orthographic task. Given that these correlations were not reported in previous works, we also conducted some exploratory correlational analyses between N1 asymmetry, age, and performance measures.

Methods

Participants. Data from 14 early Welsh/English bilinguals (6 females, mean age of 38.4 years, range 22-52 years) and 14 late learners of Welsh (10 females, mean age of 40.3 years, range 25-52 years) were included in the analyses (data from 5 additional participants were not included due to excessive noise). All participants had normal or corrected-to-normal vision; none had a history of neurological disorders and none were currently taking any neurological medications. Additional demographic information is available in Table 1. All participants were paid £7/hour for their participation. The study was approved by the appropriate ethics committees and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

INSERT TABLE 1 HERE

Based on the self-reports of the Early Bilinguals, ten learned Welsh from birth, three from age 3, and one from age 5; seven learned English from birth, two before age 3, three from age 4, and two from age 5. The primary language spoken at home until two years of age was Welsh for 6 participants, a mix of Welsh and English for four participants, and English for four participants. Elementary education was in Welsh for five participants, balanced for one participant, predominantly in Welsh for six participants, and predominantly in English for two participants. Middle school and high school instruction was in both Welsh and English for all Early Bilinguals. Participants were asked to indicate how well they felt they spoke and read Welsh and English. All participants rated themselves as native-like speakers in both languages. Eleven participants rated themselves as native-like in reading Welsh, and three participants as somewhat proficient. All participants rated themselves as native-like in reading English. Early participants reported to speak Welsh 47.5% of the time (SD=25.8) and to read Welsh for recreational reading 28% of the time (SD=26.7).

For Late Bilinguals, the primary language spoken at home until two years of age was English for 13 participants, and Polish for one participant. Elementary education was in English for all participants. English was also the only language of instruction in middle school for 11 participants (three had a predominantly English instruction with some Welsh) and in high school for 12 participants (two had a predominantly English instruction with some Welsh). Participants were then asked to indicate how well they felt they spoke Welsh and English. All participants rated themselves as native-like in English; nine participants rated themselves as native-like in Welsh, four as somewhat proficient, and one between these two levels. In terms of proficiency in reading, all participants rated themselves as native-like in English; eight participants rated themselves as native-like in Welsh, five as somewhat proficient, and one as low proficient.

Late Bilinguals reported to speak Welsh 30% of the time (SD=22.3) and to read Welsh for recreational reading 22.5% of the time (SD=14.8). These percentages were not significantly different from the Early Bilingual group (all *p*'s>0.1).

Proficiency in Welsh was also measured objectively with a translation task including all Welsh words used in the semantic categorization task (n=96). The task was administered at the end of the experimental session before the debriefing. Participants were asked to circle all the familiar Welsh words and, when possible, provide the correct English translation. The data are shown in Table 2. Altogether, Early Bilinguals were more accurate in providing the English definition of Welsh words and rated fewer words as unfamiliar than Late Bilinguals.

INSERT TABLE 2 HERE

Stimuli and materials. Two lists of 80 Welsh and 80 English words were created: 50% with high cross-language (CL) ND (CLND is defined here as the number of orthographic neighbors that a word in one language has in the other language) and 50% with low cross-language ND. Therefore, the stimuli included 40 high CLND Welsh (e.g., *bara*, *clais*, *talu*, *torth*), 40 low CLND Welsh (e.g., *awyr*, *araf*, *bwyd*, *olwyn)*, 40 high CLND English (e.g., *bail*, *nest*, *tale*, *earth*), 40 low CLND English (e.g., *beam*, *deep*, *wool*, *alive*), and animal names as probe stimuli (20% per block, n=16 for each language block). Words were four- or five-letter words, all either monosyllabic or bi-syllabic. Welsh words were selected from the Cronfa Electroneg o Gymraeg (Ellis, O'Dochartaigh, Hicks, Morgan, & Laporte, 2001); English words were selected from the CELEX database (Baayen et al., 1995). Words with at least one occurrence per million were selected and used to calculate the number of orthographic neighbors of words within and across languages. Table 3 presents means and standard deviations for the main lexical and orthographic measures regarding target (non-animal names) stimuli. In addition to CLND, bigram frequency (defined as the average bigram frequency across the entire letter string, both position and length-sensitive; Davis, 2005) was calculated based on both Welsh and English norms.

INSERT TABLE 3

The four types of target stimuli were matched in terms of length, frequency, and within-language neighbors (all *p*'s > 0.2). High and low CLND English words differed in terms of number of Welsh neighbors ($p<0.0001$, two-tailed). High CLND English words had a higher bigram frequency than low CLND English words based on Welsh norms ($p<0.0001$, two-tailed). High and low CLND Welsh words differed in terms of number of Welsh neighbors ($p<0.0001$, two-tailed). High CLND Welsh words had a higher bigram frequency than low CLND Welsh words based on English norms ($p<0.0001$, two-tailed).

Sixteen Welsh and 16 English animal names were included in each language block. They were matched on length (Welsh, mean = 4.5, SD = 0.52; English, mean = 4.43, SD = 0.51; $p=0.73$, two-tailed) and frequency (Welsh, mean = 26.56, SD = 41.64; English, mean = 15.63, SD = 29; $p=0.4$, two-tailed).

Procedure. After giving written consent and filling out the handedness and biographical questionnaires, participants were asked to perform a semantic categorization task on two Welsh and two English blocks of trials whose order of presentation was counterbalanced across participants (the Welsh and English blocks were presented twice). All participants were tested in a sound-attenuating booth. Participants were seated 100 cm directly in front of a 19-inch monitor on which stimuli were presented. The sequence of events was the following: a fixation point appeared at the center of the screen and served as a warning signal that the new trial is about to begin; after a random and variable interval between 500 and 700 ms, words were presented for 1000 ms and followed by 1000 ms of blank screen. Each trial ended with a screen indicating that participants could blink. The session was self-paced, that is, participants controlled when the next trial would begin by pressing a button on a response box. The stimuli were presented in Courier font; the longest stimulus (5-letter string) subtended four degrees of visual angle in length and two degrees of visual angle in height.

Participants were instructed to press a button every time an animal name would appear on the screen. Both speed and accuracy were stressed. Response hand was counterbalanced across participants. Two practice lists, one for each language, were created, each including ten words (two animal names). Each participant saw only one practice block, whose language was that of the first experimental block. None of the words in the practice list were included in the experimental list.

Participants were then asked to perform the translation task. Finally, they were fully debriefed, compensated, and thanked for their participation. The entire experimental session lasted between two and three hours.

ERP recording. Electrophysiological data were recorded in reference to Cz at a rate of 1 kHz from 64 Ag/AgCl electrodes placed according to the extended 10–20 convention (Neuroscan system). Impedances were kept below 7 kΩ. EEG activity was filtered on-line band pass between 0.1 Hz and 200 Hz and re-filtered off-line with a 30 Hz low pass zero phase shift digital filter. Eye-blinks were detected using the vertical electrooculogram bipolar channel. Potential variations exceeding a threshold of 20% of maximum EEG amplitude over the duration of a complete individual recording session were automatically registered as artifacts and contributed to the computing of a model blink artifact (derived from approximately 50 individual blink artifacts in each participant). Artifacts were then individually corrected by subtracting point-by-point amplitudes of the model from signals measured at each channel proportionally to local maximum signal amplitude. Eye movements, drifts, and other artifacts were removed by an algorithm that eliminated all events associated with brain waves that were larger than 75 µV or smaller than -75 µV. The percentage of accepted trials for both Late and Early Bilinguals was 88%.

Epochs ranged from −500 to 1000 ms after the onset of the critical word. Baseline correction was performed in reference to pre-stimulus activity. Individual averages were re-referenced to the global average reference offline. Behavioral data were collected simultaneously to ERP data.

Statistical analyses. Based on visual inspection of data across single subjects, the N1 was identified as the first visible negative peak with a latency between 120-170 ms, and was preceded by a P1, identified as the first positive peak with a latency between 60-120 ms. These values were confirmed by the analysis of the mean global field power measured across the scalp, which summarizes the contribution of all electrodes in the form of a single vector norm (Picton et al., 2000). Only the analyses concerning the N1 will be described here.

Group (Early Bilinguals, Late Bilinguals) was a between subject variable; Language (English, Welsh), and CLND (high, low) were repeated measure variables. N1 analyses were run on the electrodes where N1 amplitude was largest: P7/8, PO7/8, and PO9/10. In order to describe the N1 scalp distribution more precisely, the following repeated measures variables were also used: Hemisphere (left, right) and Electrode (P7/8, PO7/8, PO9/10). The dependent variables were peak mean amplitude and peak latency. ERPs elicited by words that were rated as unfamiliar by the participants were not included in the analyses[2].

N1 asymmetry was defined as the difference in N1 amplitude between the left sites and the right sites. Therefore, a left-lateralized N1 was associated with negative values. Pearson correlations were carried out between continuous variables (N1 asymmetry, Age, Years of Welsh, Translation Accuracy, RT in the categorization task, Accuracy in the categorization task, and Unfamiliar Words (number of unfamiliar words in the translation task). Education Level (ordinal variable: 1=high school; 2=college; 3=postgraduate studies) was not included in correlational analyses because of the low number of categories in each bilingual group (two in Late Bilinguals and three in Early Bilinguals). All *p*'s are reported in terms of two-tailed test. Adjusted *p* values (Greenhouse-Geisser correction) are reported for all within-subject measures with more than one degree of freedom. Significant interactions involving condition effects were followed up by simple effects analyses. Bonferroni correction (standard alpha value of .05 corrected by number of comparisons) was applied to simple comparisons.

Results

Behavioral Data

[2] Given that the present study focused on an early component hypothesized to reflect orthographic or word form processing, only words rated as familiar by the participants were included in the final analyses, regardless of whether the participants translated them correctly.

Table 4 shows the results from the categorization task. Behavioral data were analyzed with two 2x2 ANOVAs (for accuracy and RT) with Group (Late Bilinguals, Early Bilinguals) and Language (English, Welsh) as between- and within-subject factors, respectively. Participants were faster in categorizing English than Welsh words ($F(1,26)=46.7$, $p<0.0001$). Participants were also more accurate in categorizing English than Welsh words ($F(1,26)=13.12$, $p=0.001$); this main effect was qualified by a Language x Group interaction ($F(1,26)=4.36$, $p<0.05$). Follow-up analyses (alpha level adjusted to .0125 to correct for the four comparisons) revealed that Late Bilinguals were more accurate with English than Welsh words ($p=0.005$), whereas no differences in accuracy for the two languages for observed for Early Bilinguals ($p=0.16$, n.s.). Furthermore, Early Bilinguals tended to be more accurate than Late Bilinguals on Welsh words ($p=0.06$) but not on English words ($p=0.32$).

INSERT TABLE 4 HERE

ERP data

Mean grand-average ERPs over parieto-occipital, parietal, central, and fronto-central sites is shown in Figure 1 for both groups and both languages. N1 peaked around 150 ms and was maximal over the inferior parieto-occipital sites (PO7/8, PO9/10, P7/8). It was larger over the left than right hemisphere (omnibus ANOVA, $F(1,26)=16.9$, $p<0.0001$; see Figure 2) in both groups (Late Bilinguals, $F(1,13)=3.01$, $p<0.02$; Early Bilinguals, $F(1,13)=9.33$, $p<0.01$) and for both languages (Late Bilinguals: English, $F(1,13)=6.71$, $p<0.03$, Welsh, $F(1,13)=8.87$, $p<0.02$; Early Bilinguals, English, $F(1,13)=8.15$, $p<0.02$, Welsh, $F(1,13)=10.1$, $p<0.01$).

INSERT FIGURES 1 AND 2 HERE

A significant interaction between Hemisphere, Electrode, and Group ($F(2,52)=3.37$, $p<0.05$) showed that the distribution of N1 over the two hemispheres differed between groups, but follow-up analyses did not reveal any significant distributional differences. The N1 amplitude was not modulated by CLND in Early Bilinguals (all p's>.17). In Late Bilinguals, the Language x CLND interaction approached significance ($F(1,13)=4.15$, $p=0.06$) and was qualified by a significant Language x CLND x Hemisphere interaction ($F(1,13)=7.0$, $p=0.02$). Follow-up analyses revealed that, for Welsh, CLND significantly interacted with hemisphere ($F(1,13)=5.0$, $p<0.05$; see Figure 3): with an alpha level adjusted to .0125 to correct for the four possible comparisons, N1 was larger for low than high CLND words over the left hemisphere ($p=0.01$) but not over the right hemisphere ($p=.57$, n.s.). Furthermore, N1 was larger over the left than right posterior sites for both low CLND Welsh words ($p=0.003$). No CLND effects were observed for English words (all p's>0.45).[3]

[3] Although the response hand was counterbalanced across participants, we explored the effects of Response Hand on the N1 amplitude with a new set of analyses. Adding Response Hand to the omnibus ANOVA revealed a trend for N1 to be larger for Welsh than English words (Language, $F(1,24)=3.94$, $p=0.06$). This effect was qualified by a Language x Response Hand interaction ($F(1,24)=7.35$, $p=0.01$): follow-up comparisons (critical alpha = 0.0125) showed that N1 was larger for Welsh than English words in participants who responded with their right hand ($p=0.005$). This effect did not alter the N1 lateralization (Response Hand x Language x Hemisphere, $p=0.29$) and was similar for the two groups of bilinguals (Response Hand x Language x Group, $p=0.3$), although some distributional differences between the groups were present (Response Hand x Language x Electrode x Group, $F(2,48)=7.26$, $p=0.002$). Furthermore, the interaction between Hemisphere and Response Hand was not significant (p=0.56). These effects suggest that, while response-related preparation or inhibition processes affected the N1 amplitude, the effect was similar for both groups of bilinguals and did not alter the lateralization pattern of the N1.

INSERT FIGURE 3 HERE

Correlation analyses. N1 asymmetry was measured at the electrodes where N1 amplitude was largest, that is, PO7 and PO8 in Late Bilinguals, and P7 and P8 in Early Bilinguals.

Late bilinguals. A first round of correlations revealed that almost all behavioral measures correlated with age (Years of Experience, $r(14)=.65$, $p=0.01$; Translation Accuracy, $r(14)=.8$, $p=0.001$; Unfamiliar Words, $r(14)=-.78$, $p=0.001$; Accuracy in the categorization task, $r(14)=.68$, $p=0.008$; RT in the categorization task, $r(14)=.5$, $p<0.07$). Therefore, the older the participants, the longer their experience with Welsh, the higher their accuracy in both the translation and the categorization task, the lower the number of unfamiliar words in the translation task, and the longer their RT (in this case, only a trend was present).

Age did not correlate with N1 asymmetry for Welsh ($p=0.12$) or English ($p=0.4$). Interestingly, N1 asymmetry was negatively correlated with Years of Welsh ($r(14)=-0.63$, $p=0.02$): the longer the experience with Welsh, the larger the N1 asymmetry (Figure 4). A trend for significance remained after correcting for age (r(11)=-0.5, p=0.08.

INSERT FIGURE 4 HERE

Significant or marginally significant correlations was also observed between N1 asymmetry for Welsh and Translation Accuracy ($r(14)=-0.48$, $p=0.08$), Accuracy in categorization task ($r(14)=-0.55$, $p<0.05$), and Unfamiliar Words ($r(14)=.51$, $p<0.07$). All these correlations became non-significant when age was factored out (all *p's*>0.22). Finally, a robust correlation was found between N1 asymmetry for Welsh and N1 asymmetry for English ($r(14)=.94$, $p<0.0001$; see Figure 5a).

INSERT FIGURE 5 HERE

Early Bilinguals. N1 asymmetry for Welsh and English did not correlate with age (Welsh, $r(14)=-.12$, $p=0.7$; English, $r(14)=-.24$, $p=0.4$), RT in the categorization task (Welsh, $r(14)=-.35$, $p=0.22$; English, $r(14)=-.25$, $p=0.38$), Translation Accuracy ($r(14)=.12$, $p=0.68$), or Unfamiliar Words ($r(14)=-.08$, $p=0.8$). As for Late Bilinguals, a robust correlation was found between N1 asymmetry for Welsh and N1 asymmetry for English ($r(14)=.95$, $p<0.0001$; see Figure 5b).

Discussion

In both groups, words from both languages elicited a posterior N1. The negative component peaked around 150 ms and had an inferior parieto-occipital distribution as described in previous studies. Furthermore, the N1 was left-lateralized in both groups for both languages, confirming previous studies on N1 asymmetry for print (e.g., Hauk et al., 2006; Proverbio et al., 2004; Rossion et al., 2003; Simon et al., 2007; Spironelli & Angrilli, 2007, 2009). The fact that this asymmetry was found for Welsh in both Early and Late Bilinguals suggests that the engagement of the left hemisphere circuits involved in word recognition can be established regardless of when one learns to read in a second language.

In Late Bilinguals, almost all the behavioral measures in Welsh correlated with age: the older the participants, the more accurate their performance in both the categorization and the translation task. N1 asymmetry correlated with both Accuracy in the categorization task and Years of Experience with Welsh: the more accurate the participants were in the categorization task, and the more experienced with Welsh, the more the N1 was left-lateralized. Importantly, the correlation between N1 asymmetry and Years of Experience showed a trend for significance when age was partialled out. A similar result was recently observed by Spironelli and Angrilli (2009), who showed that the N1 asymmetry in monolinguals becomes more robust with age and reading experience. Studies with children have also shown that the N1 is not lateralized in young readers (Maurer et al., 2005; Spironelli & Angrilli, 2009); furthermore, recent studies with adults suggest that familiarity with a new script is associated with a right-lateralized N1 (e.g., Maurer, Blau, Yoncheva, & McCandliss, in press). These results suggest that N1 lateralization over the left posterior sites, purportedly reflecting the recruitment of the posterior left hemisphere circuits during reading, is a process that slowly develops with experience and perceptual expertise for words, in both monolinguals and bilinguals. Given that the correlation between N1 asymmetry and measures of performance observed by Spironelli & Angrilli (2009) might have been explained by age, our study is the first, to our knowledge, to suggest a correlation between an increase in N1 asymmetry and experience with a language (L2, in this case). This result will need to be confirmed by future studies employing a larger sample size.

Changes in lateralization with experience with a language have also been observed for other ERP components. For example, in a visual rhyming task with readers spanning from 8 to 23 years of age, the Contingent Negative Variation (CNV) elicited by primes before the presentation of the targets was found to become increasingly and linearly larger over the left frontal sites until 19-20 years of age (Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001). Interestingly, the CNV asymmetry correlated with the participants' reading and spelling scores: the higher the scores, the more left-lateralized the CNV. This correlation remained significant even after age was partialled out. Grossi et al. (2001) hypothesized that the CNV reflected the allocation of resources to specific anterior neural circuits in preparation for target presentation and visual rhyming, which requires post-lexical decoding skills. Both the CNV pattern in Grossi et al. (2001) and the N1 pattern in the present study reveal a dynamic and experience-driven pattern of organization for areas involved in reading.

Unlike Spironelli & Angrilli (2009), we did not find significant correlations between N1 asymmetry and age, not even when the data from the two groups were collapsed (Welsh, p=.13; English, p=.23). Similarly, in Spironelli & Angrilli (2009), the N1 lateralization was stable in young and moderately aged participants. Therefore, if we exclude shifts in lateralization driven by experience with a second language, as the ones described in the present study, it appears that the most dramatic changes in N1 asymmetry take place between childhood and adulthood.

Interestingly, we also found a strong correlation between N1 asymmetry for Welsh and N1 asymmetry for English in Late Bilinguals. On the basis of this finding alone, the correlation could indicate that the pattern of N1 lateralization for the second language simply depends on the pattern of N1 lateralization for the first language. In this view, learning a second language late in life may involve the integration of the second language into already organized circuits for word recognition. Yet, alongside our finding of a correlation between N1 asymmetry and years of language experience, it may be that learning a second language late in life might not simply entail recruiting the areas already in place for the first language, but also shape the organization of these areas, even in terms of the relative contribution of the two hemispheres (i.e., lateralization). Longitudinal studies would be useful in determining if this is the case. Individuals who start learning a second language could be tested on both the first and second language at different intervals during the training. By employing such a design, the initial pattern of lateralization for the two languages could be established and subsequent shifts in lateralization could be recorded, along with progress on behavioral measures.

The degrees of N1 asymmetry for the two languages were highly positively correlated in Early Bilinguals as well. The N1 was also left-lateralized for both languages. These participants received an education involving a combination of both languages. All rated themselves as being native-like Welsh speakers and 11 out of 14 rated themselves as native-like as Welsh readers. Therefore, these results stand in contrast with Proverbio et al. (2002), where a bilateral N1 was observed for Italian and a left-lateralized N1 for Slovenian in a group of compound bilinguals. It is important to note that, in previous studies, languages were exclusively compared in terms of hemisphere effects in ANOVA designs. We provided evidence for a robust linear relationship between the N1 lateralization in one language and N1 lateralization for the second languages. Clearly, different degrees of N1 asymmetry for the two languages do not necessarily exclude a relationship between them. Therefore, Late and Early Bilinguals showed similar and related patterns of N1 lateralization for the two languages despite dramatic differences in the modality and age of acquisition of the two languages. The meaning of such similarity remains unclear. Future research should investigate whether the correlations in the two groups reflect similar or different mechanisms depending on the age of acquisition of the second language.

N1 was larger for low than high CLND Welsh words in Late Bilinguals. This effect was absent for English words and was absent in Early Bilinguals. Words with high ND generally elicit larger ERPs than words with low ND (cross-language ND, Grossi, Savill, Thomas, & Thierry, in preparation; within-language ND, Holcomb et al., 2002; cross-language ND, Midgley et al., 2008), an effect that has been explained in terms of a more robust lexical activation due to the larger number of neighbors (Holcomb et al., 2002; Midgley et al., 2008). Here, the effect is reversed and is earlier than the effects observed by Midgley and colleagues. Furthermore, if the effect were solely due to CLND, it would be expected to be present for English words as well, assuming that the number of Welsh neighbors increases with experience. Therefore, the N1 CLND effect might reflect a different mechanism. Given that high and low CLND Welsh words also differed in terms of bigram frequency according to English norms (that is, low CLND Welsh words were formed by bigrams that were less frequent in English than those forming high CLND Welsh words; see Table 3), this effect might reflect the lower familiarity of Late Bilinguals with certain letter combinations of Welsh. From an orthographic perspective, Welsh low CLND might have “looked” less familiar than

Welsh high CLND words, and therefore more nonword-like, at least based on the more familiar English orthography. Based on this interpretation, the effect would be expected to be smaller in Late Bilinguals with many years of experience with Welsh compared to less experienced bilinguals. An independent sample *t* test carried out on Late Bilinguals based on a median split (median=12 years of experience) revealed that subjects with more experience in Welsh had a smaller CLND effect in the N1 time window (M -0.56, SD 1) than participants with fewer years of experience (M -1.38, SD 1.33), but the effect failed to reach statistical significance (p=0.2). However, size effects analyses revealed a Cohen's d of 0.7, suggesting that the size of the CLND effect in Late Bilinguals varied with years of experience with Welsh (medium-to-large effect).

More power is needed to clarify the nature of the CLND effect in the N1 time window. At any rate, the presence of this effect over the left posterior sites confirms conclusions from previous studies on the modulation and lateralization of N1 in reading. As mentioned in the Introduction, several studies have found differences in N1 amplitude between words and letter strings containing illegal combinations of letters (e.g., Cohen, et al., 2000; Compton et al., 1991; McCandliss et al., 1997; Sauseng et al., 2004). Hauk et al. (2006) also found an effect of orthographic typicality (measured as positional bigram and trigram frequency) on the N1 amplitude. These orthographic effects are usually lateralized to the left hemisphere. It is noteworthy that the N1 effect observed in the present study is not a general typicality effect, given that that high and low CLND words within each language were matched by bigram frequency. Furthermore, the effect was absent for English stimuli in Late Bilinguals and was absent in both languages in early Bilinguals. This pattern might suggest that orthographic features are processed by distinct networks for the two languages in early bilinguals, whereas in late bilinguals orthographic processing might still be driven by mechanisms set on values of letter combinations more frequent in the first language, at least in less proficient bilinguals. In this view, the larger N1 to low than high CLND Welsh words in Late Bilinguals might be interpreted as an incongruency effect.

The present data also suggest that the N1 lateralization is not related to grapheme-to-phoneme conversion mechanisms (as proposed by Maurer and McCandliss, 2007). The same pattern of lateralization was found for two languages with different orthography-to-phonology mapping (opaque for English and transparent for Welsh). A similar conclusion was reached by Maurer et al. (2008) in their study on Japanese scripts. Therefore, the lateralization of N1 seems to be explained more in terms of familiarity with the words of a language than with the degree of transparency of its orthography. However, the nature of this familiarity remains unclear. We did not include pseudowords in our study; therefore, we cannot disentangle the effects due to the familiarity with the words of a language and the familiarity with the orthography for the language. For example, Proverbio et al. (2005) found a similar left-lateralized N1 to Greek stimuli in both native Greek and naive Italian speakers, a pattern that could be explained in terms of visual similarities between letters in the Roman alphabet and letters in the Greek alphabet (Maurer et al., 2008). Left-lateralized familiarity letter effects in the 120-250-ms time window have also been found in both monolinguals and bilinguals by Wong, Gauthier, Woroch, Debuse, and Curran (2005).

The present work has several limitations that should be overcome in future studies. First, given that linguistic experiences tend to be extremely heterogeneous in both early and late bilinguals, sample size should be increased. Welsh is a “minority” language and its use varies geographically and contextually (Lyon, 1996). People born in Wales from at least one Welsh-speaking parent have Welsh as their first language, but the rate at which they use their native language varies considerably depending on a series of factors including parental support and the district’s educational policies (Lyon, 1996). This heterogeneity, paired with the existence of regional variations in Welsh vocabulary, could in part explain why some of the Early Bilinguals did not recognize a few Welsh words as familiar. Second, proficiency in Welsh should be measured with a more extensive range of tests (e.g., fluency, grammatical competence). The choice of a translation task in this study was motivated by our interest in orthographic and lexical processing. However, word translation might not capture some important aspects of linguistic proficiency, even in terms of vocabulary. Words are learned and used in context and translation is not a frequent activity for most regular bilinguals (word-to-word translation is actually more frequent in second language learning settings, which might in part explain the little difference between Late and Early Bilinguals on the translation task; Grosjean, 2008). The use of borrowed forms is also frequent in early or native bilinguals when they speak to other bilinguals (Grosjean, 2008), and this might have reduced their confidence with certain Welsh words in the present study. Furthermore, not all words in one language have a clear correspondent translation in the other language (Oller, 2005). Finally, future studies should include a wider range of words. The major purpose of our study was to investigate cross-language interactions in bilinguals by manipulating cross-language neighborhood density; as neighborhood density is inversely proportional to word length (e.g., Hauk et al., 2006), only short words were selected to guarantee two balanced sets of stimuli with an appropriate number of high and low CLND words.

In conclusion, the present data add to the extant literature in showing (1) A strong positive correlation between the degrees of N1 asymmetry for L1 and L2 processing in both Late and Early Bilinguals, and (2) A correlation between N1 asymmetry for Welsh words and years of experience with L2 in Late Bilinguals. A fuller functional interpretation of these correlations will require further investigation.

References

Assadollahi, R., & Pulvermüller, F. (2003). Early influences of word length and frequency: a group study using MEG. *NeuroReport*, *14* (8), 1183-1187.

Baayen, R. H., Piepenbrock, R., and Gulikers, L. (1995). The CELEX Lexical Database (Release 2). Linguistic Data Consortium, Philadelphia.

Bentin, S., Allison T., Puce, A., Perez, E., & McCarthy, G. (1996). Electrophysiological studies of face perception in humans. *Journal of Cognitive Neuroscience, 8*, 551-565.

Bentin, S., Muochetant-Rostaing, Y., Giard, M.H., Echallier, J.F., Pernier, J. (1999). ERP manifestations of processing printed words at different psycholinguistic levels: time course and scalp distribution. *Journal of Cognitive Neuroscience, 11*, 235–260.

Brem, S., Halder, P., Bucher, K., Summers, P., Martin, E., & Brandeis, D. (2009. Tuning of the visual word processing system: Distinct developmental ERP and fMRI effects. *Human Brain Mapping, 30*, 1833-1844.

Cohen, L., Dehaene, S., Naccache, L., Lehericy, S., Dehaene-Lambertz, G., Henaff, M.-A., et al. (2000). The visual word form area: spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. *Brain*, *123*, 291-307.

Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance VI* (pp. 535-555). New York: Academic Press.

Compton, P.E., Grossbacher, P., Posner, M.I., & Tucker, D.M. (1991). A cognitive-anatomical approach to attention in lexical access. *Journal of Cognitive Neuroscience*, *3*(4), 304-312.

Davis, C. J. (2005). N-Watch: A program for deriving neighborhood size and other psycholinguistic statistics. *Behavior Research Methods, 37*, 65-70.

Ellis, N. C., & Hooper, A. M. (2001). Why learning to read is easier in Welsh than in English: Orthographic transparency effects evinced with frequency-matched tests. *Applied Psycholinguistics (Psychological Studies of Language Processes), 22* (4), 571-599.

Ellis, N. C., O'Dochartaigh, C., Hicks, W., Morgan, M., & Laporte, N. (2001). Cronfa Electroneg o Gymraeg/A 1 million word lexical database and frequency count for Welsh. University of Wales Bangor: School of Psychology. Available at http://www.bangor.ac.uk/ar/cb/ceg.php.en.

Genesee, F., Hamers, J., Lambert, W. E., Mononen, L., Seitz, M., & Stark, R. (1978). Language processing in bilinguals. *Brain and Language, 5*, 1–12.

Grosjean, F. (2008). *Studying Bilinguals*. Oxford, UK: Oxford University Press.

Grossi, G., & Coch, D. (2005). Automatic word form processing in masked priming: an ERP study. *Psychophysiology, 42* (3), 343-355.

Grossi, G., Coch, D., Coffey-Corina, S., Holcomb, P. J., & Neville, H. J. (2001). Phonological processing in visual rhyming: A developmental study. *Journal of Cognitive Neuroscience 13*, 610–625.

Grossi, G., Savill, N., Thomas, E., & Thierry, G. (in preparation). Electrophysiological cross-language neighborhood effects in early and late English-Welsh bilinguals.

Hauk, O., Davis, M. H., Ford, M., Pulvermüller, F., & Marslen-Wilson, W. D. (2006). The time course of visual word recognition as revealed by linear regression analysis of ERP data. *NeuroImage, 30*, 1383-1400.

Hauk, O., & Pulvermüller, F. (2004). Effects of word length and frequency on the human event-related potential. *Clinical Neurophysiology, 115* (5), 1090-1103.

Kim, K. H., & Kim, J. H. (2006). Comparison of spatiotemporal cortical activation pattern during visual perception of Korean, English, Chinese words: An event-related potential study. *Neuroscience Letters, 394*, 227–232.

Kim, K. H., Yoon, H. W., & Park, H. W. (2004). Spatiotemporal brain activation pattern during word/picture perception by native Koreans. *NeuroReport, 15* (7), 1099-1103.

Kucera, H., & Francis, W.N. (1967). Computational analysis of present-day American English. Providence: Brown University Press.

Lyon, J. (1996). *Becoming Bilingual. Language Acquisition in a Bilingual Community*. Clevedon, UK: Multilingual Matters.

Maurer, U., Brem, S., Bucher, K., & McCandliss, B. D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience, 17* (10), 1532–1552.

Maurer, U., Blau, V. C., Yoncheva, Y. N., McCandliss, B. D. (in press). N170 in learning to read a novel script: early visual familiarity enhances right lateralization. *Developmental Neuropsychology*.

Maurer U., Brandeis D., & McCandliss, B. D. (2005). Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response. *Behavioral and Brain Functions*, 1:13.

Maurer, U., Zevlin, J. D., & McCandliss, B. D. (2008). Left-lateralized N170 effects of visual expertise in reading: Evidence from Japanese syllabic and logographic scripts. *Journal of Cognitive Neuroscience, 20* (10), 1878-1891.

Maurer, U., & McCandliss, B. D. (2007). The development of visual expertise for words: the contribution of electrophysiology. In E. L. Grigorenko & A. J. Naples (Eds.), *Single-word reading: biological and behavioral perspectives*. Mahwah, NJ: Lawrence Erlbaum Associates.

McCandliss, B. D., & Noble, K. G. (2003). The Development of Reading Impairment: a Cognitive Neuroscience Model. *Mental Retardation and Developmental Disabilities Research Reviews*, *9* (3), 196-204.

McCandliss, B. D., Posner, M. I., & Givon, T. (1997). Brain plasticity in learning visual words. *Cognitive Psychology, 33*, 88-110.

Neville, H. J., Mills, D. L., & Lawson, D. S. (1992). Fractionating language: Different neural subsystems with different sensitive periods. *Cerebral Cortex, 2*, 244-258.

Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, *9*, 97-113.

Oller, K. (2005). The distributed characteristic in bilingual learning. In J. Cohen, K. T. McAlister, K. Rolstad, and J. MacSwan (Eds.), *Proceedings of the 4th International Symposium on Bilingualism*, pp. 1744-1749. Somerville, MA: Cascadilla Press.

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, J., R., et al. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology, 37*, 127-152.

Proverbio, A. M., Čok, B., & Zani, A. (2002). Electrophysiological measures of language processing in bilinguals. *Journal of Cognitive Neuroscience*, *14* (7), 994-1017.

Proverbio, A. M., Del Zotto, M., & Zani, A. (2005). Greek language processing in naive and skilled readers: Functional properties of the VWFA investigated with ERPs. *Cognitive Neuropsychology*, *23* (3), 355-375.

Proverbio, A. M., Vecchi, L., & Zani, A. (2004**).** From orthography to phonetics: ERP measures of grapheme-to-phoneme conversion mechanisms in reading. *Journal of Cognitive Neuroscience*, *16* (2), 301-317.

Proverbio, A. M., Zani, A., & Adorni, R. (2008). The left fusiform area is affected by written frequency of words. *Neuropsychologia*, *46*, 2292–2299.

Rossion, B., Joyce, C. J., Cottrell, G. W., Tarr, M. J. (2003). Early lateralization and orientation tuning for face, word and object processing in the visual cortex. *NeuroImage*, *20*, 1609-1624.

Sauseng, P., Bergmann, J., & Wimmer, H. (2004). When does the brain register deviances from standard word spellings? – An ERP study. *Cognitive Brain Research, 20*, 529-532.

Sereno, S. C., Brewer, C. C., & O'Donnell, P. J. (2003). Context effects in word recognition: Evidence for early interactive processing. *Psychological Science, 14,* 328-333.

Sereno S. C., Rayner K., & Posner M. I. (1998). Establishing a time-line of word recognition: evidence from eye movements and event-related potentials. *NeuroReport 9* (10), 2195-2200.

Simon, G., Petit, L., Bernard, C., & Rebaï, M. (2007). N170 ERPs could represent a logographic processing strategy in visual word recognition. *Behavioral and Brain Functions, 3* (21), 1-11. Open Access, available at http://www.behavioralandbrainfunctions.com/content/3/1.

Spironelli, C., & Angrilli, A. (2007). Influence of Phonological, Semantic and Orthographic tasks on the early linguistic components N150 and N350. *International Journal of Psychophysiology*, *64*, 190–198.

Spironelli, C., & Angrilli, A. (2009). Developmental aspects of automatic word processing: Language lateralization of early ERP components in children, young adults and middle-aged subjects. *Biological Psychology, 80*, 35-45.

Tanaka, J. W., & Curran, T. (2001). A neural basis for expert object recognition. *Psychological Science*, 12, 43-47.

Tarkiainen, A., Helenius, P., Hansen, P. C., Cornelissen, P. L., & Salmelin, R. (1999). Dynamics of letter string perception in the human occipitotemporal cortex. *Brain, 122*, 2119 – 2132.

Vogel, E. K., & Luck, S. J. (2000). The visual N1 component as an index of a discrimination process. *Psychophysiology, 37*, 190-203.

Wong, A. C.-N., Gauthier, I., Woroch, B., Debuse, C., & Curran, T. (2005). An early electrophysiological potential associated with expertise in letter perception. *Cognitive, Affective, and Behavioral Neuroscience*, *5,* 306-318.

Wydell, T. N., Vuorinen, T., Helenius, P., & Salmelin, R. (2003). Neural correlates of letter-string length and lexicality during reading in a regular orthography. *Journal of Cognitive Neuroscience, 15* (7), 1052-1062.

Figure Captions

1. Mean grand-average ERPs over parieto-occipital, parietal, central, and fronto-central sites for both bilingual groups and both languages. Differences between English and Welsh were much larger in Late than Early Bilinguals for the late ERP components (a full description of these effects is discussed in Grossi et al., in preparation). Negative is plotted up.

2. Mean grand-average ERPs over parieto-occipital sites for both bilingual groups and both languages. Negative is plotted up.

3. Interaction between CLND and Hemisphere for Welsh words in Late Bilinguals. N1 was larger for low than high CLND Welsh words at the left hemisphere sites. Bars indicate S. E. M.

4. Correlation between N1 asymmetry and Years of Welsh in Late Bilinguals. N1 asymmetry is expressed in μV.

5. Correlation between N1 asymmetry and Years of Welsh in Late Bilinguals A. Late bilinguals; B. Early Bilinguals. N1 asymmetry is expressed in μV.

Table 1. Summary of participants' information (means and SD are shown for continuous variables).

	Age	Handedness†	Level of Instruction	Years of Welsh*	Age of Acquisition (Welsh)*
Late Bilinguals (n=14, 10 females)	40.3 (range 25-52, SD=9.7)	14 right-handed	4 university, 10 post-graduate	11.9 (6.9)	28.3 (8.7)
Early Bilinguals (n=14, 6 females)	38.4 (range 22-52, SD=9.6)	12 right-handed, 1 left-handed, 1 ambidextrous	2 high school, 7 university, 5 post-graduate	37.4 (10.2)	1 (1.7)

* *p*<0.0001

† Based on Oldfield (1971)

Table 2. Participants' performance in the translation of the Welsh stimuli (means and standard deviations). Accuracy reflects the percentage of correct responses on both animal targets and critical words.

Translation Task (Welsh)	Correct*	Incorrect	Familiar	Unfamiliar*
Late Bilinguals (n=14)	80.73 (16.6)	2.38 (1.8)	5.66 (4.8)	11.24 (12.7)
Early Bilinguals (n=14)	91.15 (9.4)	1.86 (3.5)	3.42 (4.8)	3.57 (5.9)

*p=0.05

Table 3. Characteristics of stimuli (means and standard deviations)

Targets	**Length**	**Written frequency***	**CL ND**	**WL ND**	**BF English**	**BF Welsh**
English (high CL ND)	4.28 (0.45)	71.7 (75.2)	7.9 (2.1)	9.23 (5.45)	28.22 (9.1)	29.92 (7.61)
English (low CL ND)	4.35 (0.48)	75.45 (83.21)	0.23 (0.6)	8.35 (4.35)	29.03 (12.36)	14.3 (5.9)
Welsh (high CL ND)	4.2 (0.4)	74.1 (72.27)	7.83 (3.93)	9.63 (2.78)	25.1 (9.2)	27.2 (7.2)
Welsh (low CL ND)	4.33 (0.47)	75.6 (70.24)	0.4 (0.63)	9.33 (2.79)	13.16 (12.52)	24.71 (6.26)

CL = Cross-Language; WL = Within-Language; ND = Neighborhood Density; BF = Bigram Frequency

*Based on Kucera & Francis (1967) for English and Ellis et al. (2001) for Welsh.

Table 4. Participants' performance in the categorization task (means and standard deviations). Accuracy reflects the percentage of correct responses on animal targets.

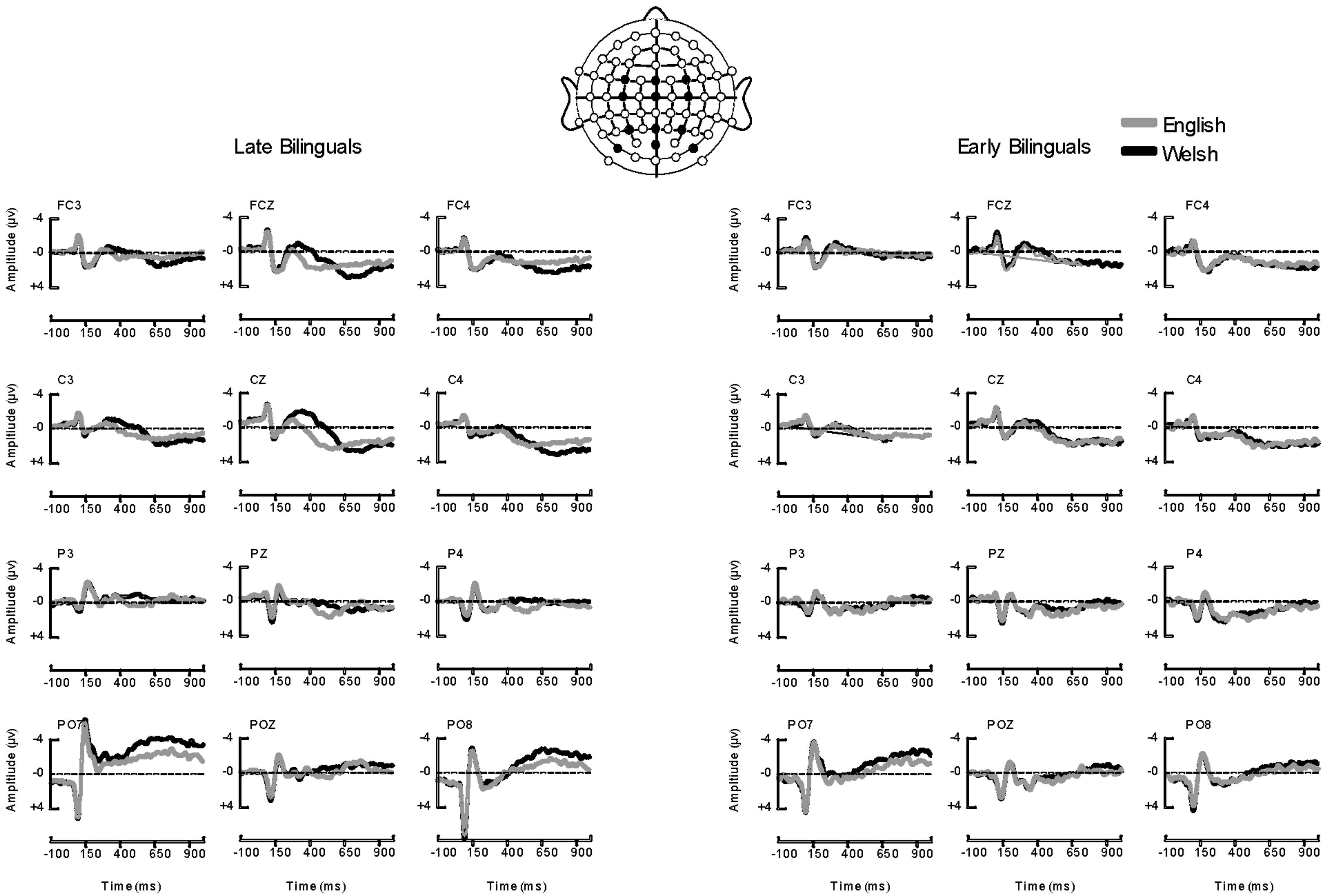
Categorization Task	Accuracy English	RT English	Accuracy Welsh	RT Welsh
Late Bilinguals (n=14)	99.1 (1.9)	575 (74.5)	84.2 (16.7)	666.4 (76.1)
Early Bilinguals (n=14)	98.2 (2.7)	565 (64.5)	94.2 (9.5)	619.3 (73)

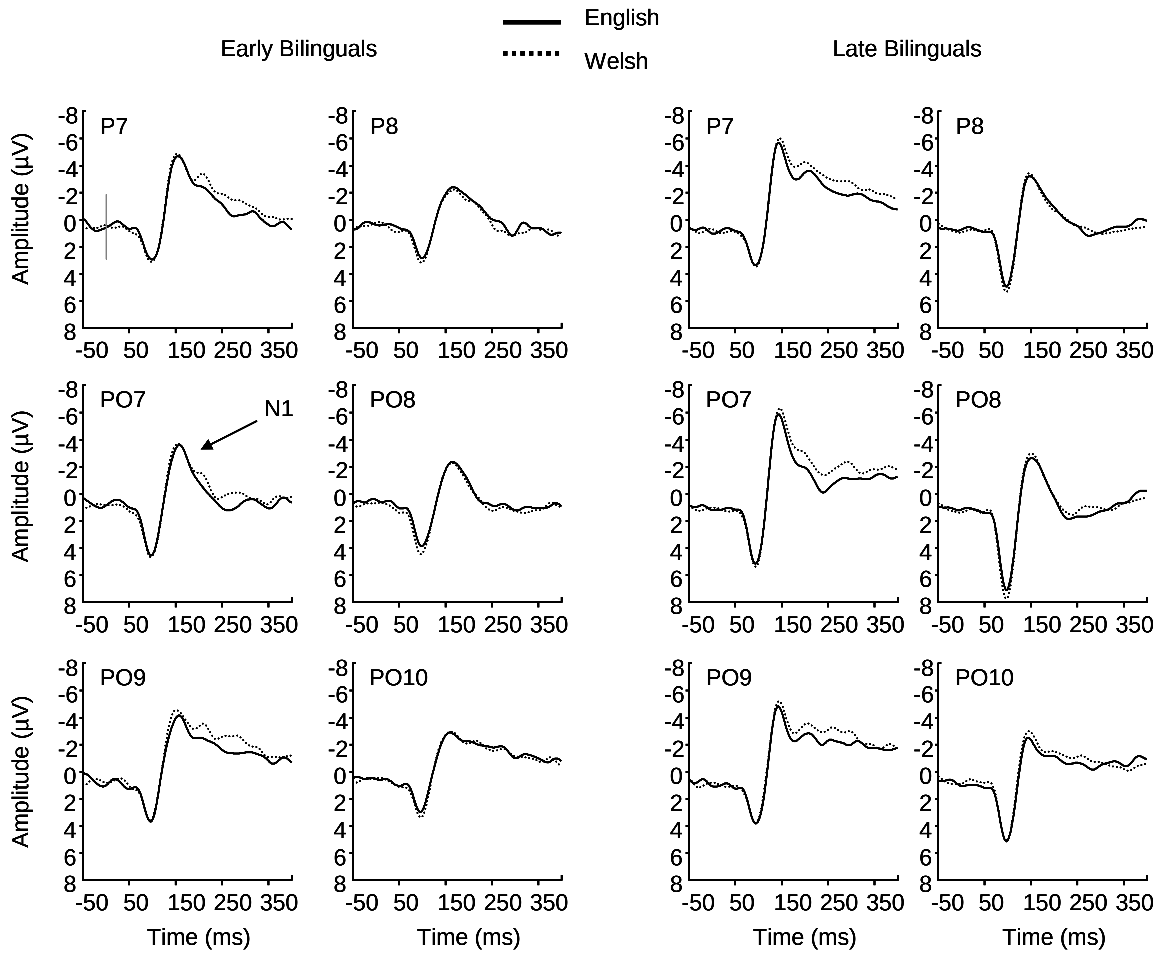
Appendix – Stimulus List

Welsh (Low CLND)	Welsh (High CLND)	English (Low CLND)	English (High CLND)
aden (*wing*)	bara (*bread*)	beam	bail
araf (*slow*)	cais (*attempt, try*)	sack	bard
awyr (*air, sky*)	caws (*cheese*)	deep	bell
balch (*proud*)	clais (*bruise*)	duke	best
bryn (*hill*)	cloi (*to lock*)	fear	card
bwyd (*food*)	coes (*leg*)	flag	care
cawr (*giant*)	cors (*swamp, marsh*)	flow	cart
croyw (*fresh, clear*)	cread (*creation*)	free	cent
crwn (*round*)	curo (*to beat*)	hood	clay
cryf (*strong*)	dail (*leaves*)	jump	crew
cwyr (*wax*)	eang (*wide*)	kind	dead
deon (*dean*)	glaw (*rain*)	seam	gain
diod (*to drink*)	grawn (*grain, berries*)	loop	hair
drych (*mirror*)	gwin (*wine*)	cake	hell
dwyn (*to steal, take*)	haid (*to swarm*)	ripe	hero
garw (rough)	loes (*woe, pain*)	rope	lawn
geni (*to be born*)	nain (*grandmother*)	mask	mass
gofod (*space*)	nant (*stream, valley*)	slow	nest
gwag (*empty*)	pais (*petticoat*)	snow	pain
gwair (*grass, hay*)	parc (*park*)	wave	pale
gwau (*to weave, knit*)	pell (*far*)	wear	path
gwres (*heat*)	poen (*pain*)	week	pawn

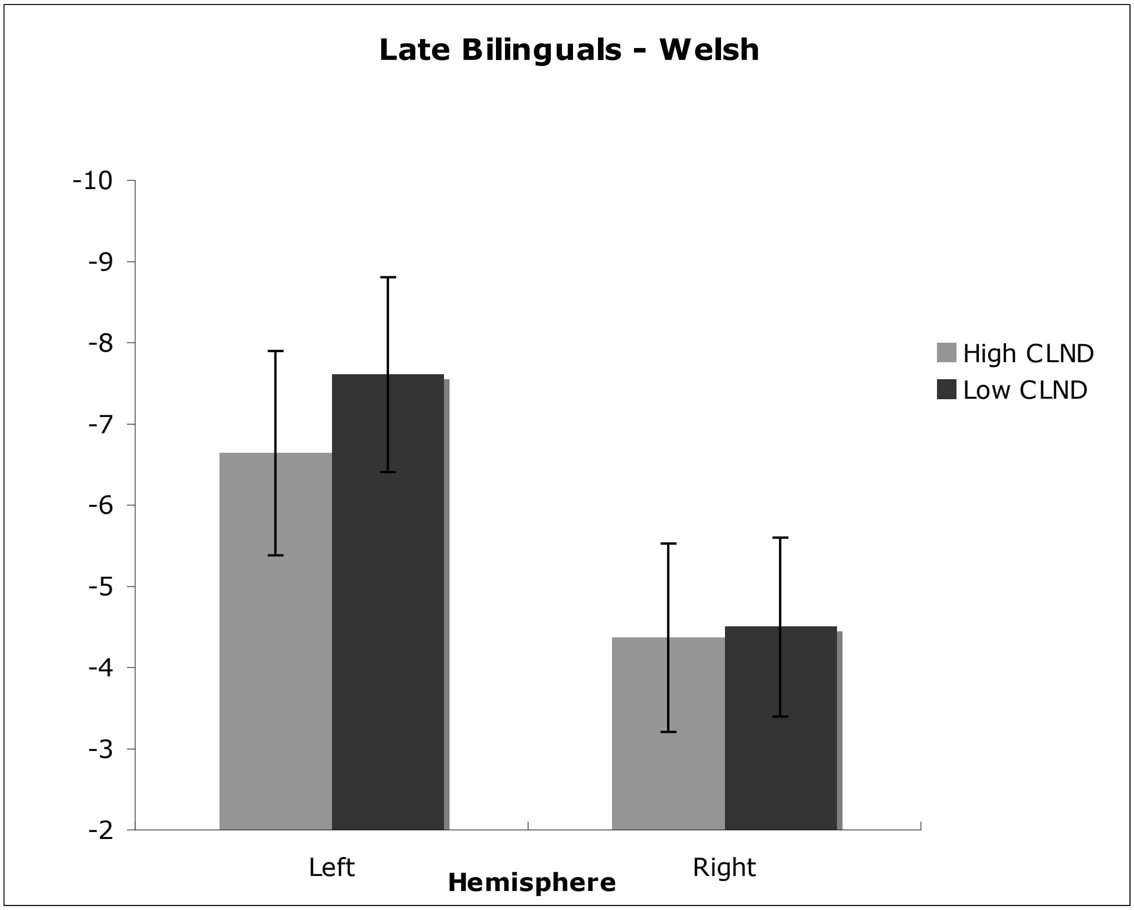
haen (*layer*)	poer (*to spit*)	weep	rest
hafod (*farm, cabin*)	pont (*bridge*)	wind	shot
hogan (*girl*)	porth (*gate, doorway*)	wine	tale
hufen (*cream*)	pren (*wood, tree*)	wool	tall
hwyr (*late*)	pres (*brass, bronze*)	alive	test
maer (*mayor*)	sain (*sound*)	alone	toes
magu (*to rear*)	sant (*saint*)	black	trim
moel (*bald*)	sied (*shed*)	blame	basin
olwyn (*wheel*)	sioe (*show*)	board	baton
piau (*to own*)	stad (*estate*)	plane	berth
rhes (*row, line*)	tair (*three*)	coast	cross
rhos (*moor*)	talu (*to pay*)	eight	earth
saer (*carpenter*)	torf (*crowd*)	floor	faint
siec (*cheque*)	torth (*loaf*)	funny	paint
taeru (*to insist*)	trais (*violence*)	peach	perch
tagu (*to choke*)	trist (*sad*)	tired	towel
tocyn (*ticket*)	wagen (*wagon*)	shame	woman
truan (*miserable*)	wats (*watch*)	shore	worth

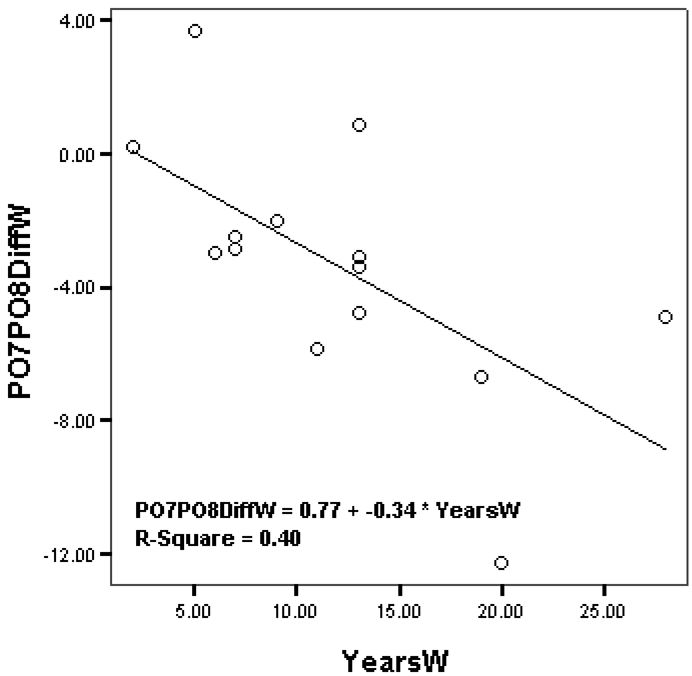
Figure(s)


Late Bilinguals
Early Bilinguals
English
Welsh
FC3
FCZ
FC4
C3
CZ
C4
P3
PZ
P4
PO7
POZ
PO8
Amplitude (µv)
-4
-0
+4
-100
150
400
650
900
Time (ms)

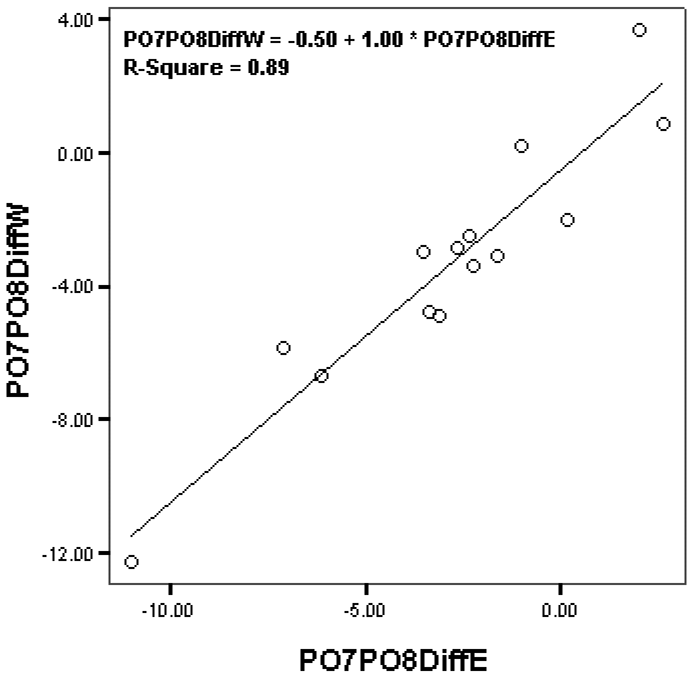


English
Welsh
Early Bilinguals
Late Bilinguals
P7
P8
PO7
PO8
PO9
PO10
N1
Amplitude (µV)
Time (ms)
-8
-6
-4
-2
0
2
4
6
8
-50
50
150
250
350


Late Bilinguals - Welsh
-10
-9
-8
-7
-6
-5
-4
-3
-2
High CLND
Low CLND
Left
Right
Hemisphere

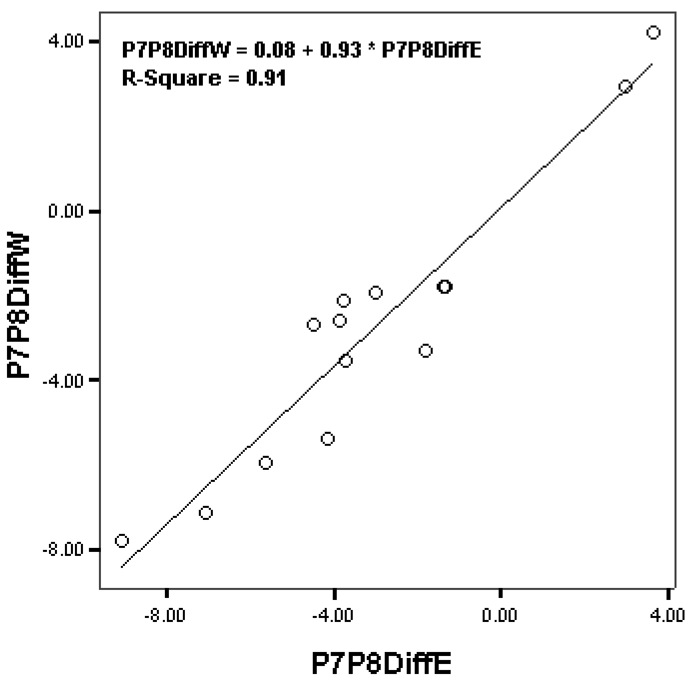

PO7PO8DiffW = 0.77 + -0.34 * YearsW
R-Square = 0.40
4.00
0.00
-4.00
-8.00
-12.00
5.00
10.00
15.00
20.00
25.00
PO7PO8DiffW
YearsW

A.



PO7PO8DiffW = -0.50 + 1.00 * PO7PO8DiffE
R-Square = 0.89
4.00
0.00
-4.00
-8.00
-12.00
PO7PO8DiffW
-10.00
-5.00
0.00
PO7PO8DiffE

B.



P7P8DiffW = 0.08 + 0.93 * P7P8DiffE
R-Square = 0.91
4.00
0.00
-4.00
-8.00
P7P8DiffW
-8.00
-4.00
0.00
4.00
P7P8DiffE