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Spatiotemporal Distribution of Cortical Processing of First and Second Languages in Bilinguals. II. Effects of Phonologic and Semantic Priming

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Abstract: This study determined the effects of phonology and semantics on the distribution of cortical activity to the second of a pair of words in first and second language (mixed pairs). The effects of relative proficiency in the two languages and linguistic setting (monolinguistic or mixed) are reported in a companion paper. Ten early bilinguals and 14 late bilinguals listened to mixed pairs of words in Arabic (L1) and Hebrew (L2) and indicated whether both words in the pair had the same or different meanings. The spatio-temporal distribution of current densities of event-related potentials were estimated for each language and according to semantic and phonologic relationship (same or different) compared with the first word in the pair. During early processing (<300 ms), brain activity in temporal and temporoparietal auditory areas was enhanced by phonologic incongruence between words in the pair and in Wernicke's area by both phonologic and semantic priming. In contrast, brain activities during late processing (>300 ms) were enhanced by semantic incongruence between the two words, particularly in temporal areas and in left hemisphere Broca's and Wernicke's areas. The latter differences were greater when words were in L2. Surprisingly, no significant effects of relative proficiency on processing the second word in the pair were found. These results indicate that the distribution of brain activity to the second of two words presented bilingually is affected differently during early and late processing by both semantic and phonologic priming by- and incongruence with the immediately preceding word. *Hum Brain Mapp 34:2882–2898, 2013.* © 2012 Wiley Periodicals, Inc.

Key words: event-related potentials; hemispheres; bilingualism; proficiency; incongruence

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INTRODUCTION

Bilingualism, Critical Periods, and Proficiency

Although "bilingual" refers to anyone using two or more languages or dialects in everyday life [Grosjean, 1994], neuropsychological studies suggest that the interaction of the two languages in the bilingual brain produces a bilingual entity that is different than its monolingual constituents [Grosjean, 1989]. Bilinguals use the two languages, separately or together, for different purposes, in different circumstances. Because of this diversity in use, bilinguals are rarely equally fluent in the two languages.

Bilinguals are usually labeled as early and late, according to the age of second language (L2) acquisition. Early bilinguals are usually equally proficient in the two languages [as measured by tests such as COWAT - Controlled Oral Word Association Test; Benton and Hamsher, 1976] while late bilinguals are more proficient in the language they acquired first (L1). There is no sharp cutoff point where the ability to acquire "perfect" language skills begins and ends and no well-defined critical period for L2 acquisition was found. However, the period before 7 (sometimes 6 or 5) years old is considered the optimal period to acquire native-like second language [Flege et al., 1999; Johnson and Newport, 1991; Lenneberg, 1967].

Factors Affecting Distribution of Processing L1 and L2

Previous studies differ on whether first and second language employ overlapping or different brain networks. Electrophysiological evidence suggests different cortical areas for processing L1 and L2 [Ojemann and Whitaker, 1978; Roux and Tremoulet, 2002; Simos et al., 2001] while fMRI and PET [Abutalebi and Green, 2007; Chee et al., 1999; Hernandez et al., 2000; Klein et al., 1999] indicate overlapping distributions. However, the time course of activity in brain networks involved in processing L1 and L2 has rarely been addressed. fMRI and PET allow accurate localization of brain activity, but their low temporal resolution may not detect brain areas that are only briefly activated.

A combined magnetoencephalography and magnetic resonance imaging study compared language processing in bilingual adults and found two time periods that showed differences between L1 and L2 [Leonard et al., 2010]. Processing L1 words involved a typical left-lateralized sequence of activity, while words in L2 activated right cortex more strongly from ~135 ms, and this activation was attenuated when words became familiar with repetition. At ~400 ms, L2 responses were generally later than L1 and more bilateral.

The adaptive nature of brain networks suggests that the circumstances in which L1 and L2 are used modify the distribution of brain processing. In a companion study (Pratt et al., 2012), the distribution of brain activities during processing words that were presented only in L1 or only in L2 (monolinguistic setting) were compared with the distributions of processing words in a mixed setting in which both L1 and L2 words were presented. The study found that cortical activities were larger in mixed than monolinguistic settings among early bilinguals but lower in mixed than in monolinguistic settings among late bilinguals, but this effect was modified by the immediately preceding word, particularly among late bilinguals. Earlier studies on the effects of context on language processing among bilinguals [e.g., Abutalebi et al., 2008a; Elston-Guttler et al., 2005a,b; de Groot et al., 2000; Kerkhofs et al., 2006; Wu and Thierry, 2010] related to reading or picture naming, i.e., visual representations of language. However, processing L2 was shown to activate the auditory, but not the visual, representation of language among bilinguals, even when visual presentation was used [Wu and Thierry, 2010], compatible with an auditory primary modality of language. In this study, we focused on the effects of phonologic and semantic context with the immediately preceding word and its interactions with proficiency and language.

Purpose of This Study

The aims of this study were to determine whether the distribution and time course of processing spoken words in L1 and L2 is modified by the semantic and phonologic similarity of the word with an immediately preceding word and whether these effects are different between languages (L1 or L2) and levels of linguistic proficiency (early or late bilinguals).

We used auditory presentations of words, the primary modality of language, in a paradigm that required comparison of words in a pair [Sinai and Pratt, 2002]. We varied the semantic and phonologic similarity as well as the language of the two words in each pair (see later section). The languages used were Hebrew and Arabic, which have similar phonologies, enabling word pairs with similar phonology and same or different meaning. This choice of phonologically similar languages reduced a possible confound by phonologic differences between languages.

We analyzed the distributions of brain activity during processing the second words in the pair for the effects of language proficiency (early vs. late bilinguals), language (L1 vs. L2), and the semantic and the phonologic congruence of the words in the pair (same vs. different). We hypothesized that early processing in temporal areas will be more affected by phonologic incongruence and priming while late processing in temporal and temporoparietal auditory areas and in Wernicke's and Broca's areas will be more sensitive to semantic incongruence, as suggested by N_{400} and P_{550} event-related potentials studies [e.g., Kutas et al., 2011].

METHODS

Subjects

Twenty-four (10 women and 14 men) 18 to 25 years old right-handed normal hearing subjects participated in the study. All subjects were tested for level of bilingualism using a Controlled Oral Word Association Test [COWAT; Benton and Hamsher, 1976] to determine their level of verbal fluency in Hebrew and Arabic. The Hebrew COWAT used three letters (Bet, Gimmel, and Shin) in the phonemic part and three semantic categories (animals, fruits and vegetables, vehicles) in the semantic part. The Arabic COWAT also used three letters (Jim, Fa, and E'in) in the phonemic part and the same three categories (animals, fruit and vegetables, vehicles) for the semantic part. All subjects were Israeli Arabs with a high-school matriculation diploma attending a university, who grew up speaking Arabic and were proficient in Hebrew as well. However, the acquisition of Hebrew differed, depending on the community in which they were raised: Some grew up in an Arabic-speaking community (e.g., small village), where Hebrew is only studied in public school (late bilinguals), while others were raised in a mixed community (e.g., big city), where they were exposed to Hebrew and used it with neighbors years before attending public school (early bilinguals). Ten of the subjects (6 women and 4 men, mean age = 21.2 years, SD = 3.2) were defined as Arabic–Hebrew early bilinguals, based on acquisition of both languages before the age of 6 years, and on their Arabic/Hebrew COWAT score ratio of 0.8 (SD = 0.2). This ratio confirms these subjects' report on feeling comfortable speaking and reading both Hebrew (slightly more) and Arabic (slightly less), using Arabic at home and Hebrew in most everyday dealings outside the home. Fourteen of the subjects (4 women, 10 men, mean age = 20.9 years, SD = 2.0) were defined as Arabic–Hebrew late bilinguals, based on acquisition of Hebrew past the age of 8, in the public school system, and on their average Arabic/Hebrew COWAT score ratio of 1.4 (SD = 0.3). This ratio confirms these subjects' report on feeling more comfortable speaking Arabic than Hebrew; using Arabic at home and in most interactions outside the home, whereas Hebrew was used only when necessary outside home (e.g., university studies). Subjects were paid for their participation and all procedures were approved by the institutional review board for experiments involving human subjects (Helsinki Committee).

Stimuli

Subjects listened to pairs of frequent bisyllabic words (nouns) in Arabic and Hebrew, spoken by a male native speaker of the respective language. Having a different speaker for each language alleviated subjects' confusion regarding which language they heard or confusing translation between languages as repetition of the same word in the same language. Avoiding these types of confusion alleviated the possible use of different processing strategies for phonologically similar or different word pairs. Each pair consisted of an Arabic word and a Hebrew word. Hebrew words were selected from a standardized list of frequent words in elementary school level children's books, while in Arabic, in the absence of standardized lists, words were selected by a jury of five native Arabic speakers to have comparable frequency of use among elementary school children. The jury also labeled the words as phonologically similar or different than Hebrew words. The words selected consisted of consonants common to both languages (e.g., avoiding /p/ which does not exist in Arabic; or /th/ which is absent in Hebrew). The number of different words in each language from which the pairs of words were drawn, i.e., the word inventory for each language, was 89.

Half the pairs consisted of words that sounded differently (phonologically different) and their meanings were either the same, i.e., they were translations based on dictionary entries (e.g., "*shoolkhan*" in Hebrew and "*tauleh*" in Arabic, both meaning "*table*") or different (e.g., "*khalon*" which means "*window*" in Hebrew and "*jajeh*" which means "*chicken*" in Arabic). The remaining 50% of the pairs were similarly sounding (phonologically similar), while their meanings could either be the same (50%), i.e., they were translations (e.g., "*bayit*" meaning "*house*" in both languages) or different (e.g., "*akhbar*," meaning "*news*" in Arabic and "*mouse*" in Hebrew). Thus, pairs consisted of four combinations of semantic and phonologic similarity with equal (25%) probability: semantically and phonologically similar (similarly sounding translation), semantically similar and phonologically different (different-sounding translation), semantically different and phonologically similar (different meaning but similarly sounding) and semantically and phonologically different (no semantic relation or similar sound). Words that were homonyms in both languages were avoided when not in a phonologically similar role. Half the pairs had a Hebrew first word and Arabic second word and the other pairs began with an Arabic word followed by a Hebrew word.

The duration of each word in the pair was between 500 and 700 ms, and the interval between words in a pair was 800 ms. The interval between offset of a pair and the onset of the following pair was 1000 ms, such that the time interval between onset of a pair and onset of the subsequent pair was 3 s. These short within- and between-pair intervals were chosen to make the easy task of translating very simple words more challenging. We verified that the within pair and between pair intervals were distinct enough to avoid confusion which was the first and which was the second word in a pair.

Procedure

Twenty-two 9-mm silver disc electrodes were placed according to the 10-20 system at: F_{p1}, F_7, F_3, F_z, F_4, F_8, F_{p2}, T_3, C_3, C_z, C_4, T_4, T_5, P_3, P_z, P_4, T_6, O_1, O_2, 1.5 cm above the left and right mastoids (M'_1 and M'_2), all referenced to the center of the chin, to record the electroencephalogram (EEG). The mastoidal electrodes were placed 1.5 cm above their standard positions to avoid distortion due to deviations from sphericity in the source estimation procedures. In addition, an electrode below the left eye, referenced to F_z, was used to monitor eye movements (EOG). In total, EEG was recorded from 21 electrodes and EOG was recorded from one diagonal differential recording below the left eye referenced to F_z. An electrode over the 7th cervical spinous process served as ground. Impedance across each electrode pair was maintained below 5 kΩ.

Subjects were seated in a comfortable reclining armchair in a sound-proof chamber and were instructed to listen to pairs of words and indicate by an appropriate button press whether both words in the pair had the same or different meaning, regardless of their language (two alternative forced choice semantic decision). Because a button press was required across all conditions, a possible motor contribution to brain activity in response to the second word in the pair did not confound the effects of experimental conditions.

Pairs of words were presented in three settings: (1) all pairs consisted of two words in Arabic (Arabic monolinguistic setting); (2) all pairs consisted of two words in Hebrew (Hebrew monolinguistic setting); and (3) all pairs randomly consisted of an Arabic word followed by a Hebrew word, or a Hebrew word followed by an Arabic word (mixed linguistic setting). The session order was the same across all subjects to begin with the easier L1 and then proceed with L2. The mixed condition was presented last so the monolinguistic conditions will not be confounded by subjects treating the semantics in the session's language with phonologically similar words of the other language. Having L1 first, followed by L2 and then the mixed setting could, potentially, contribute to an overall language-related effect. However, in the absence of subjects reporting fatigue and the counterbalancing of fatigue by a training effect during the session, we considered a significant order confound unlikely. These considerations and the need to always have the mixed condition last, as detailed earlier, dictated the order of settings to begin with L1, followed by L2 with the mixed setting—last.

Data Acquisition

Potentials from the EEG (×100,000) and EOG (×20,000) channels were amplified, digitized with a 12 bit A/D converter at a rate of 256 samples/sec, filtered (0.1–100 Hz, 6 dB/octave slopes) and stored for off-line analysis. EEG processing began with segmentation of the continuous EEG to epochs beginning 100 ms before until 1,400 ms after each word onset. Eye movement correction [Attias et al., 1993] and artifact rejection (±150 μV) followed segmentation. Average waveforms were then computed for potentials evoked by the second word in the pair, separately for each language (Arabic and Hebrew) and for trials associated with correct positive responses (semantic congruence) and negative responses (semantic incongruence), and separately for second words that were phonologically similar or different than the preceding first word. Thus, averaged waveforms were distinguished by their language, phonologic similarity with the first word (words that sound the same or different in both languages) and semantic similarity (same or different meaning). In total, there were eight separate second word averages (two languages × two phonologic similarities × two semantic similarities). In all, between 130 and 165 trials associated with correct responses were averaged to obtain the potentials evoked by second words in each experimental condition from each subject. After averaging, the data were bandpass filtered (FIR rectangular low-pass filter with a cutoff at 24 Hz) and baseline (average amplitude during 100 ms before word onset) corrected.

ERP Functional Imaging

Standardized Low Resolution Electromagnetic Tomographic Analysis [sLORETA; Pascual-Marqui, 2002, 2009; Pascual-Marqui et al., 1994] was the functional electrophysiological brain imaging method to estimate the distribution of current density in the brain based on the scalp distribution of potentials. sLORETA makes no assumptions on the number of concurrently active sources, which is crucial in higher brain functions with their parallel processing, and it was therefore selected for this study. Sources are suggested by minimum norm constraints and a three-shell spherical head model. The solution space is restricted to cortical gray matter and hippocampus, with 6430 voxels at 5-mm spatial resolution that are registered to the Stereotaxic Atlas of the Human Brain [Talairach and Tournoux, 1988]. The sLORETA method is thus a properly standardized discrete, three-dimensional distributed, linear, minimum norm inverse solution of intracranial sources of scalp recorded potentials. The particular form of standardization used in sLORETA results in exact localization of test point sources, yielding images of standardized current density with exact localization, albeit with low spatial resolution (i.e., neighboring neuronal sources will be highly correlated). The detailed description of the method can be found in Pascual-Marqui [2002] and its exact, zero-error localization property has been proven [Pascual-Marqui, 2009]. Furthermore, sLORETA has no localization bias even in the presence of measurement and biological noise, an improvement over previously developed tomography—LORETA. sLORETA has been validated in several simultaneous EEG/fMRI studies [Mobascher et al., 2009; Olbrich et al., 2009], and in an EEG localization study for epilepsy [Rullmann et al., 2009]. Specifically, sLORETA was applied on the ERP records to image the estimated source current density throughout the duration of the brain potentials for each of the eight experimental conditions of second words, as detailed earlier.

Statistical Analyses

The task included auditory presentation of two words in sequence. When a first word in a pair is presented there is no reference for similarity between words because the second word has not been presented yet. Therefore, semantic and phonologic similarity between words could only affect processing of the second word, so analysis related only to second word processing. The estimated source current density distributions in response to the second word in the pair were analyzed in two ways: (1) the significance of differences in current density distributions at specific time intervals between pairs of experimental conditions; (2) the effects of experimental factors on the integrated activity of brain areas during time periods that were consistently active across subjects, words, and experimental conditions.

Pairwise comparisons of current density distributions

Differences in current density distributions between pairs of experimental conditions across all subjects were assessed using Statistical non-Parametric Mapping (SnPM), a common tool in functional imaging comparisons. SnPM estimates the probability distribution by using a randomization procedure, corrects for multiple comparisons and has the highest possible statistical power [Nichols and Holmes, 2002]. The SnPM method in the context of ERP source estimation was validated in our earlier studies by comparing its results with more conventional ANOVA results [Laufer and Pratt, 2003; Sinai and Pratt, 2003]. Specifically, in this study, we used the "pseudo-t" statistic which reduced noise in the data by averaging over adjacent voxels [Nichols and Holmes, 2002]. Because this procedure only corrects for multiple voxel comparisons at a single point in time, but does not address multiple comparisons in the time domain, we applied a Bonferroni-type correction in the time domain, requiring that significance is maintained over a period of 11 time points (44 ms, five time points before and five after a peak of activity). Thus, differences were considered significant if SnPM comparisons were significant ($P < 0.05$) either across 11 consecutive time points in each comparison, or using the average current density of these 11 time points.

Analysis of variance procedures

Current density values were also analyzed using repeated measures analysis of variance, for the effects of four factors: Subject group (early bilinguals, late bilinguals); Language (Hebrew, Arabic); Hemisphere (left, right); and Phonologic and Semantic similarity (Phonologically and Semantically similar, Phonologically and Semantically different, Phonologically different and Semantically similar, Phonologically similar and Semantically different).

The brain regions analyzed were the five cortical areas that were consistently found most active across experimental conditions in comparable time windows: frontal/pre-frontal areas (including BA 9, 10, 11, and 47), lateral and inferior temporal lobe (covering BA 20 and 21), temporal and temporoparietal auditory cortices (BA 40, 41, and 42), as well as around Broca's area (BA 44) and Wernicke's area (corresponding to BA 22). For each cortical area, source current density was integrated (current density × time, i.e., "area under the curve') for each of the four time periods following word onset which were consistently found to be the most active across a number of brain areas (Figs. 5 and 6) and were similarly affected by experimental manipulations. For example, although the early processing period (<300 ms) showed a few sub-peaks, only two periods 60–180 ms and 180–300 ms were differentially affected and were thus analyzed separately. Typically, the time periods defined this way also corresponded to scalp recorded components. Early processing included two periods: 60–180 ms and 180–300 ms (roughly corresponding to P_{60}-N_{125} and P_{200}, respectively); and late processing periods were 260–540 ms and 540–660 ms (roughly corresponding to N_{430} and P_{600} on the scalp). Further discussion of the selection of time windows is provided in the companion report (Pratt et al., 2012; discussed in later section). Detailed results on the analysis of the ERP waveform components are provided separately [Abu Amneh-Abbasi, 2009].

Probabilities below 0.05, after Greenhouse-Geisser corrections for violations of sphericity (when deemed necessary) and Bonferroni (all pairwise) multiple comparison post-hoc tests, were considered significant. The Results section only lists main effects, interactions and post-hoc analyses that were statistically significant.

RESULTS

General Overview

Both reaction time and accuracy were affected by semantic similarity (same vs. different meaning) between first and second words in the pair. Accuracy was also affected by phonologic similarity (same vs. different sound) of second words with the preceding first word. The potentials evoked on the scalp of both subject groups in response to second words in the pair (Figs. 1 and 2) included a sequence of P_{60}, N_{120}, P_{200}, N_{430}, and P_{600}. Source current densities of the scalp recorded potentials were derived (Figs. 3 and 4) and the effects of semantic and phonologic similarity on intracranial activity were assessed (Table I) for the five most active brain areas during four time periods defined by the time course of intracranial activity (Figs. 5 and 6).

The effects of experimental conditions on brain activity were analyzed by time periods and for each period—by brain regions. In general, the effects observed were independent of proficiency (no group main effects or interactions) and language and hemispheric lateralization of activity interacted with phonologic and semantic similarity to the first word in the same manner for both subject groups. Phonologic and semantic similarity was generally associated with higher early (<300 ms) current density (priming) to L1 words and in the left hemisphere. During late (>300 ms) processing higher current density was associated with semantic difference (incongruence), also in the left hemisphere, but more so to L2 words. A general summary of the results relating to the study's hypotheses is provided at the end of the Results section.

Behavioral Results

Reaction times ranged between 690 and 920 ms and accuracy levels ranged between 63% and 90% across all

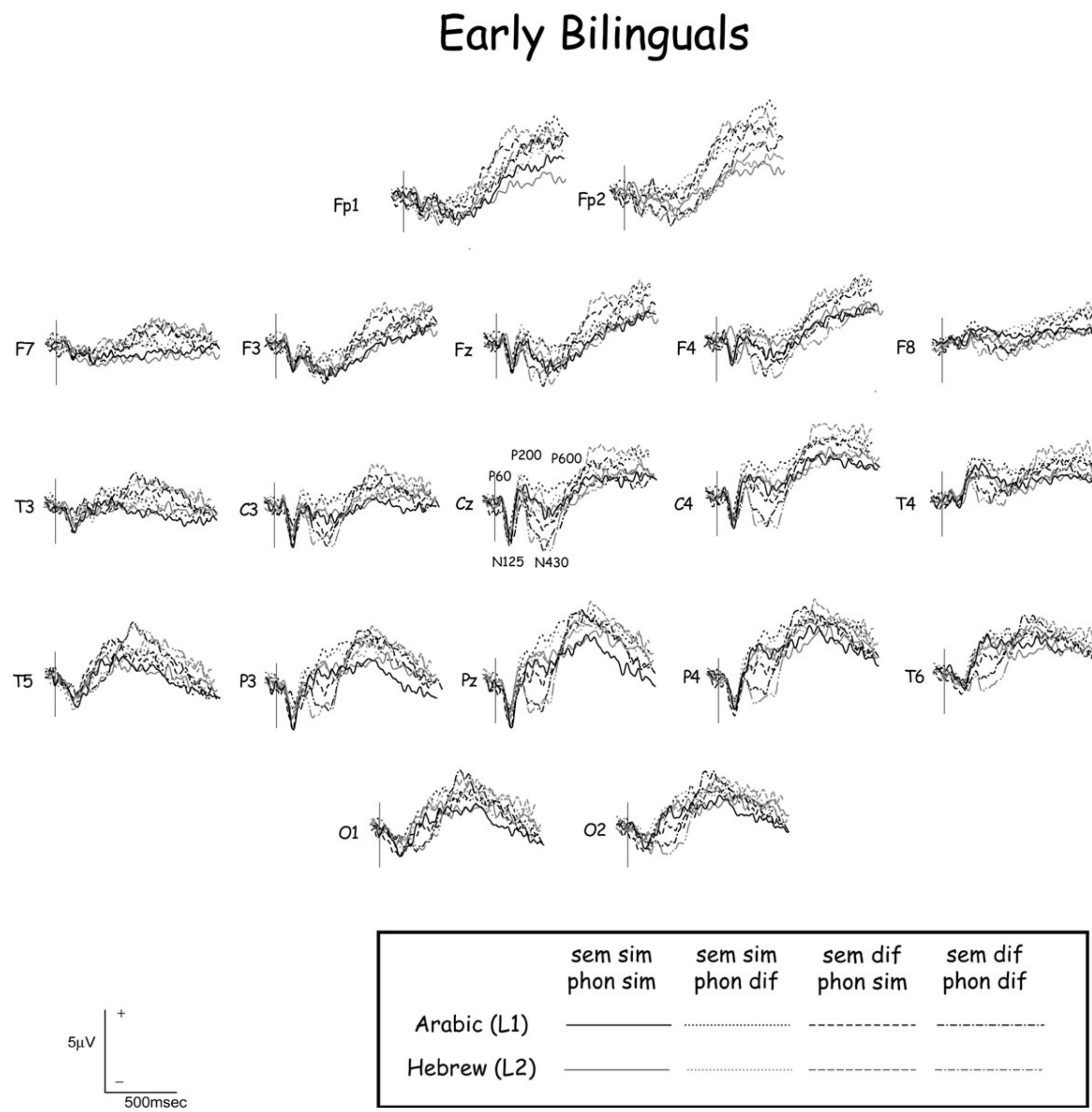

Figure 1.

Potentials to the second words in L1 (Arabic) and L2 (Hebrew) that were semantically (sem) different (dif) and phonologically (phon) similar (sim), semantically similar and phonologically different, semantically and phonologically similar, and semantically and phonologically different than the preceding first words in the pair, among early bilinguals. The vertical lines close to the beginning of traces mark the timing of word onset. Note the more negative frontal waveforms among late bilinguals, but otherwise similar peak latencies to those of early bilinguals.

experimental conditions and subject groups. Although reaction times among early bilinguals tended to be shorter than among late bilinguals, the effect of relative proficiency and its interaction with semantic and phonologic similarity did not reach significance. Performance accuracy was significantly [F (1, 232) = 11.81, $P < 0.001$] higher when second words were semantically similar (83%) than when they were different (78%) than the preceding first words in the pair; and the corresponding reaction times (760 and 820 ms, respectively) were significantly [F (1, 232) = 12.17, $P < 0.001$] shorter. Performance accuracy was also significantly [F (1, 232) = 6.41, $P < 0.01$] higher to second words that were phonologically different than the first words (81%) compared with when they were similar (79%).

Electrophysiological Results

The effects of proficiency (subject group: early vs. late bilinguals), phonologic and semantic similarity (same vs. different) with the first word, language (L1-Arabic vs.

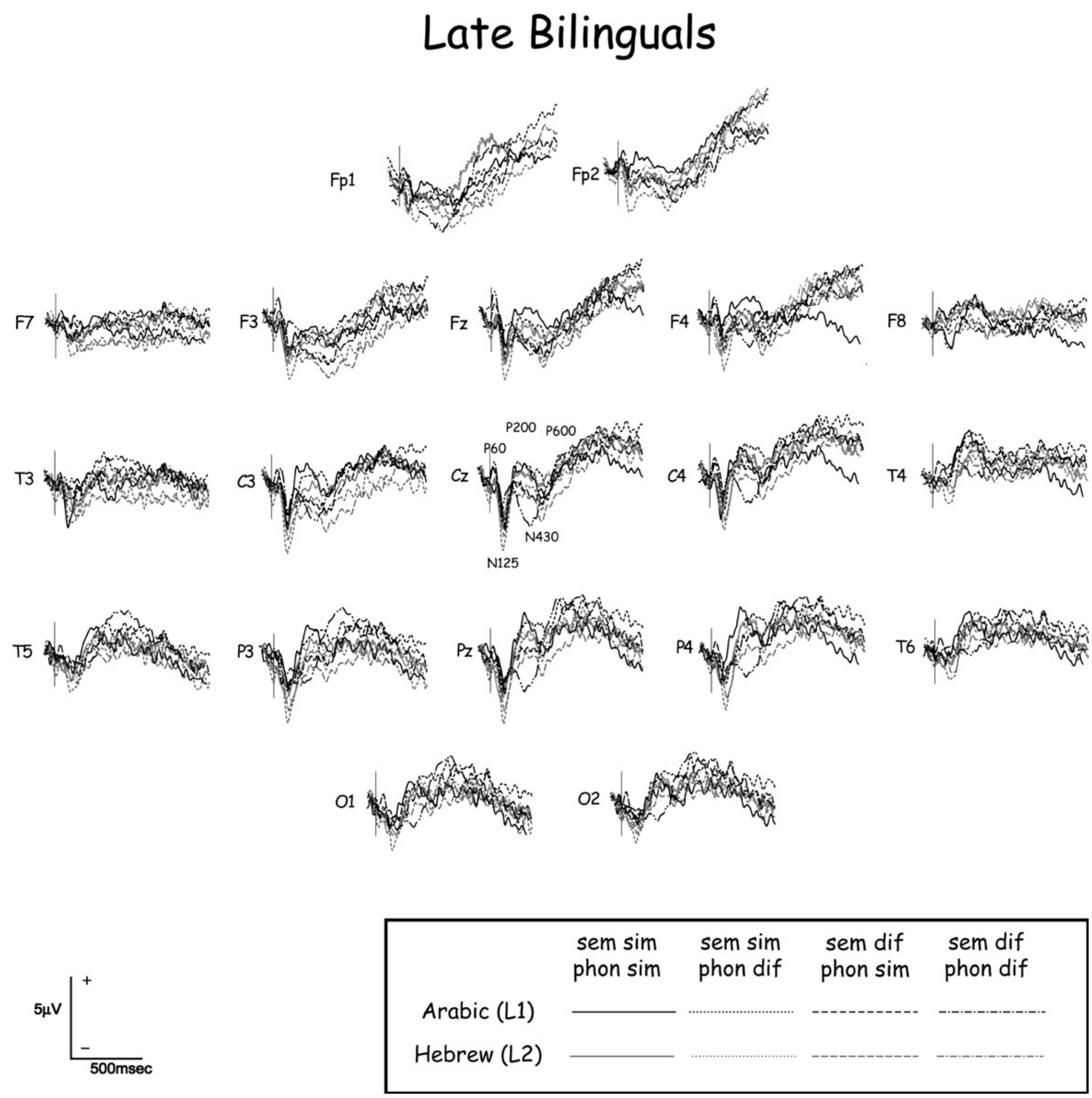

Figure 2.

Potentials to the second words in L1 (Arabic) and L2 (Hebrew) that were semantically (sem) different (dif) and phonologically (phon) similar (sim), semantically similar and phonologically different, semantically and phonologically similar, and semantically and phonologically different than the preceding first words in the pair, among late bilinguals. The vertical lines close to the beginning of traces mark the timing of word onset. Note the more negative bias of waveforms among late bilinguals, but otherwise similar peak latencies to those of early bilinguals.

L2-Hebrew), and hemisphere (Left vs. right cerebral hemisphere) on source current densities in response to second words in the pair were analyzed and the significant results are detailed in Table I. The results are detailed in the table by time periods (designated by Roman numerals) and within each time period – by brain regions (marked alphabetically). Listings in the table are referred by their column and row in the table (e.g., ID for effects on Broca's area between 60 and 180 ms). Interestingly, subject group was not involved in any main effect or interaction, implying that the effects observed were independent of proficiency. Observing Table I, no significant effects were observed in frontal and prefrontal areas in any of the time periods, and no significant effects were observed during 180–300 ms in any of the brain areas.

During 60–180 ms

Current density in lateral and inferior temporal areas (IB) was affected by an interaction manifesting in

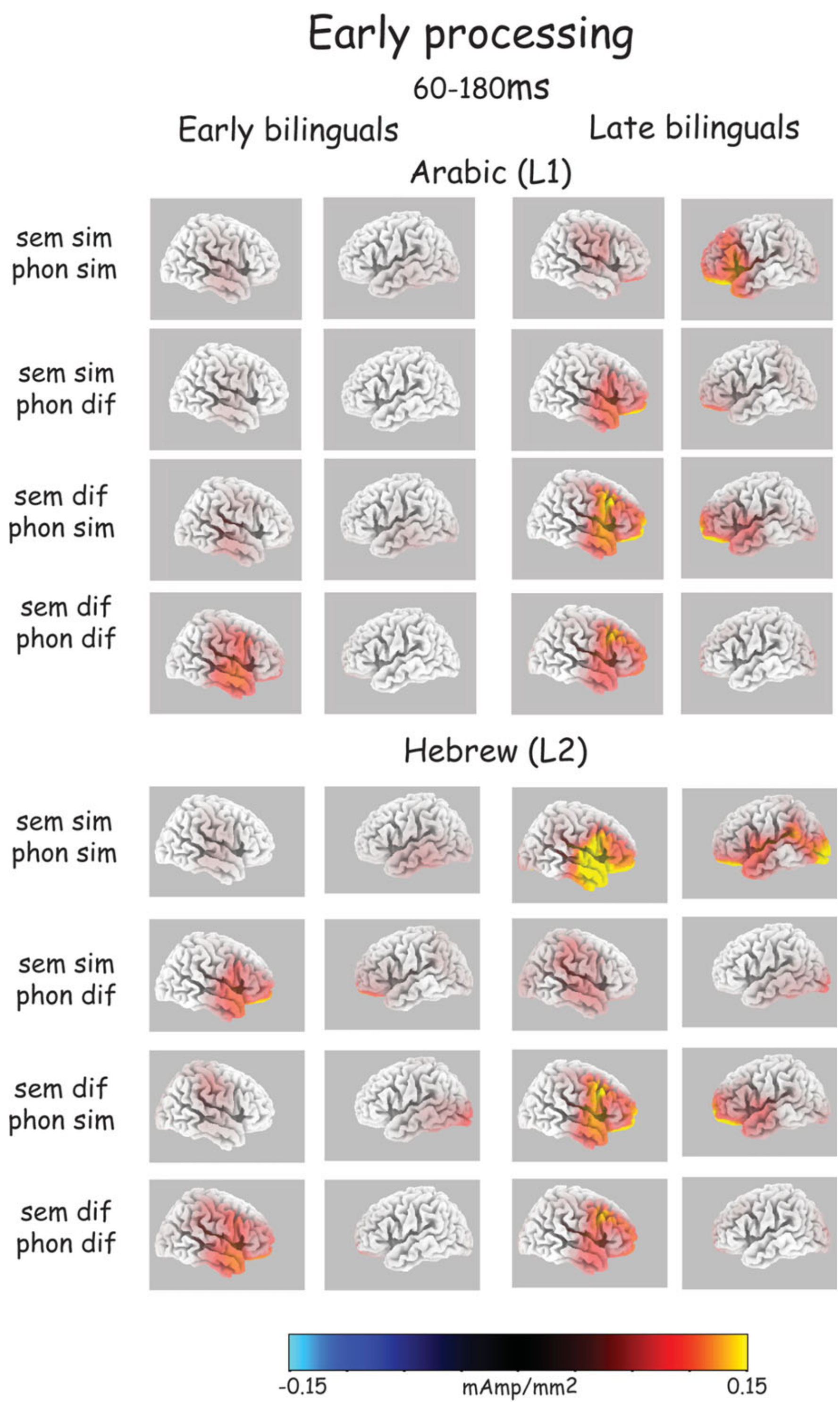

Figure 3.
Source current density distributions during 60–180 ms, in response to the second words in L1 (Arabic) and L2 (Hebrew), in early and late bilinguals (during N_{125} in the waveforms depicted in Figs. 1 and 2). Note the higher current densities to L1 than to L2, and the right hemisphere prominence of activity among early bilinguals. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

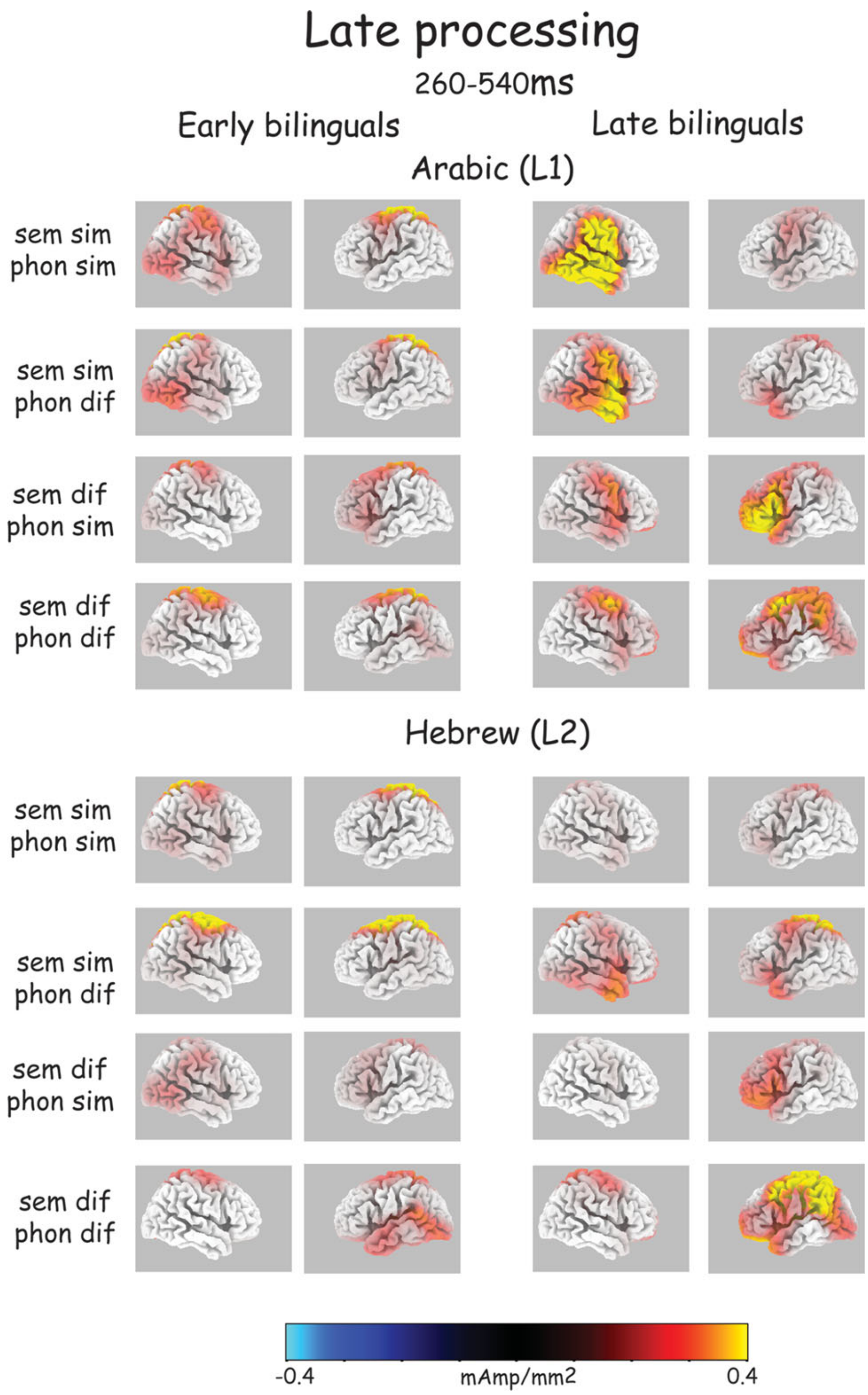

Figure 4.

Source current density distributions during 260–540 ms, in response to the second words in L1 (Arabic) and L2 (Hebrew), among early and late bilinguals (during N_{430} in the waveforms depicted in Figs. 1 and 2). Potentials to second words that were semantically different but phonologically similar and semantically similar but phonologically different compared with the first word preceding them are compared. Note the effects of phonologic and semantic similarities as well as language, which are particularly evident among late bilinguals. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE I. Significant effects (in *Italics*) of language (*Lang:* L1-Arabic vs. L2-Hebrew), hemisphere (*Hem:* Left vs right cerebral hemisphere) and semantic and phonological (*Sem* and *Phon*) similarity or difference (*Sim* or *Dif*) compared with the first word, on current densities in response to second word in the pair during four time periods in five brain areas

	I (60–180 ms)	II (180–300 ms)	III (260–540 ms)	IV (540–660 ms)
A: Frontal/prefrontal (BA 9, 10, 11, 47)				
B: Lateral/inferior temporal (BA 20, 21)	*SemPhon* × *Lang*[a] ($F = 3.75$, $P < 0.02$)			*Phon* and *SemDif*> *Other* ($F = 5.78$, $P < 0.002$) *SemPhon* × *Lang*[b] ($F = 2.88$, $P < 0.05$)
C: Temporal/temporoparietal auditory (BA 40, 41, and 42)	*SemPhon* × *Lang*[c] ($F = 4.43$, $P < 0.008$)		*Phon* and *SemDif* > *Other* ($F = 2.77$, $P < 0.05$) *SemPhon* × *Hem*[d] ($F = 5.68$, $P < 0.002$)	*Phon* and *SemDif* > *Other* ($F = 13.10$, $P < 0.001$)
D: Broca's (BA 44)			*SemPhon* × *Hem*[e] ($F = 3.22$, $P < 0.03$)	*Phon* and *SemDif* > *Phon* and *SemSim* ($F = 4.35$, $P < 0.008$)
E: Wernicke's (BA 22)	*SemPhon* × *Hem*[f] ($F = 2.86$, $P < 0.05$) *SemPhon* × *Lang*[g] ($F = 4.33$, $P < 0.009$)		*SemPhon* × *Hem*[d] ($F = 3.54$, $P < 0.03$)	*Phon* and *SemDif* > *Other* ($F = 7.30$, $P < 0.001$) *SemPhon* × Lang[b] ($F = 3.65$, $P < 0.02$)

All F values had (3, 56) degrees of freedom. Rt, Right; Lt, Left; *Other* represents all other phonological-semantic combinations.
[a]*PhonDifSemSim* < all others in L1, *PhonDifSemSim* < all others in L2.
[b]*Phon* and *SemDif* > all others in L2, less so in L1.
[c]*PhonDifSemSim* in L2 > *PhonDifSemSim* in L1, all others are the same for L1 and L2.
[d]*Phon* and *SemDif* > all others in Lt, *Phon* and *SemDif* ≈ all others in Rt.
[e]*PhonSimSemDif* > all others in Lt, *PhonSimSemDif* ≈ all others in Rt.
[f]*Phon* and *SemSim* > all others in Lt, *Phon* and *SemSim* < all others in Rt.
[g]*Phon* and *SemSim* > all others in L1, *Phon* and *SemSim* < all others in L2.

phonologically different and semantically similar second words in L1 having lower values than all other conditions, whereas when the second word was in L2, no significant differences were found between conditions. In temporal and temporoparietal auditory areas (IC) this interaction manifested in higher current densities to phonologically different and semantically similar second words in L2 than their counterparts in L1, whereas all other combinations of phonologic and semantic similarities were the same for L1 and L2. In Wernicke's area (IE) this interaction of phonologic/semantic similarity with language resulted in phonologically and semantically similar words in L1 having higher values than all other conditions, whereas in L2 they were associated with the lowest current densities compared with all other conditions. In addition, an interaction of phonologic/semantic similarity with hemisphere (IE) indicated that phonologically and semantically similar words were associated with higher current densities compared with all other conditions in the left hemisphere, and lower values than all other conditions in the right hemisphere.

During 260–540 ms

Current densities in temporal and temporoparietal auditory areas (IIIC) in response to second words that were phonologically and semantically different than the first word were higher than to all other similarity conditions. In these auditory areas as well as in Wernicke's area (IIIE), phonologically and semantically different words were associated with higher current densities than all other conditions in the left hemisphere, whereas in the right hemisphere they were not different. In Broca's area (IIID) in the left hemisphere current densities were higher in response to phonologically similar and semantically different second words compared with all other conditions, while in the right hemisphere they were not different.

During 540–660 ms

In the lateral and inferior temporal lobe (IVB), in the temporal and temporoparietal auditory areas (IVC) and in Wernicke's area (IVE), current densities in response to phonologically and semantically different second words were higher than in all other conditions. In Broca's area (IVD), current densities in response to second words that were semantically and phonologically different were higher than when they were phonologically and semantically similar. In lateral and inferior temporal lobe (IVB) and in Wernicke's area (IVE), activity in response to phonologically and semantically different words in L2 was higher than all other conditions, and this difference was diminished when words were in L1.

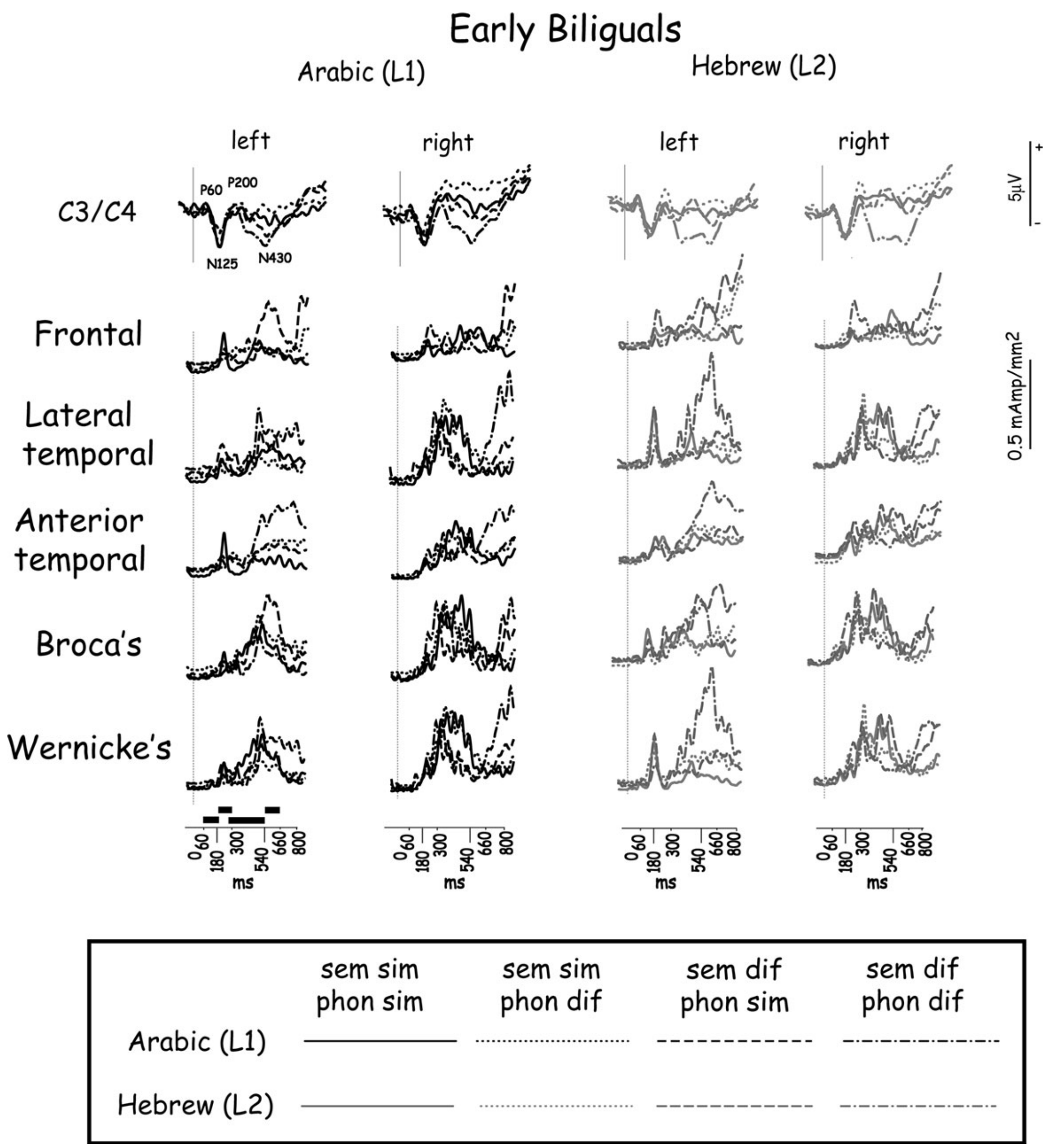

Figure 5.

Scalp potentials (C_3 and C_4, top row) and estimated source current density time courses at the five brain areas studied in the left and right hemispheres of early bilinguals in response to second words in L1 (Arabic, left 2 columns) and L2 (Hebrew, right 2 columns) that were semantically (sem) different (dif) and phonologically (phon) similar (sim), semantically similar and phonologically different, semantically and phonologically similar and semantically and phonologically different than the preceding first words in the pair, Vertical dashed lines mark word onset. Bars along the time scale mark the four time periods across which current densities were integrated for statistical analysis.

SnPM comparisons of current density distributions found some effects among late bilinguals that were absent among early bilinguals: Among late bilinguals second words that were phonologically and semantically similar to the first words in the pair were associated with left frontal areas early (∼150 ms) activity and Broca's area late activity (∼400 ms) that had higher current densities in L1 than L2. In addition, late bilinguals' late activity (∼400 ms) to L2 words had higher current densities in left frontal and Wernicke's areas when they were semantically different than when they were semantically and phonologically similar to the first word in the pair.

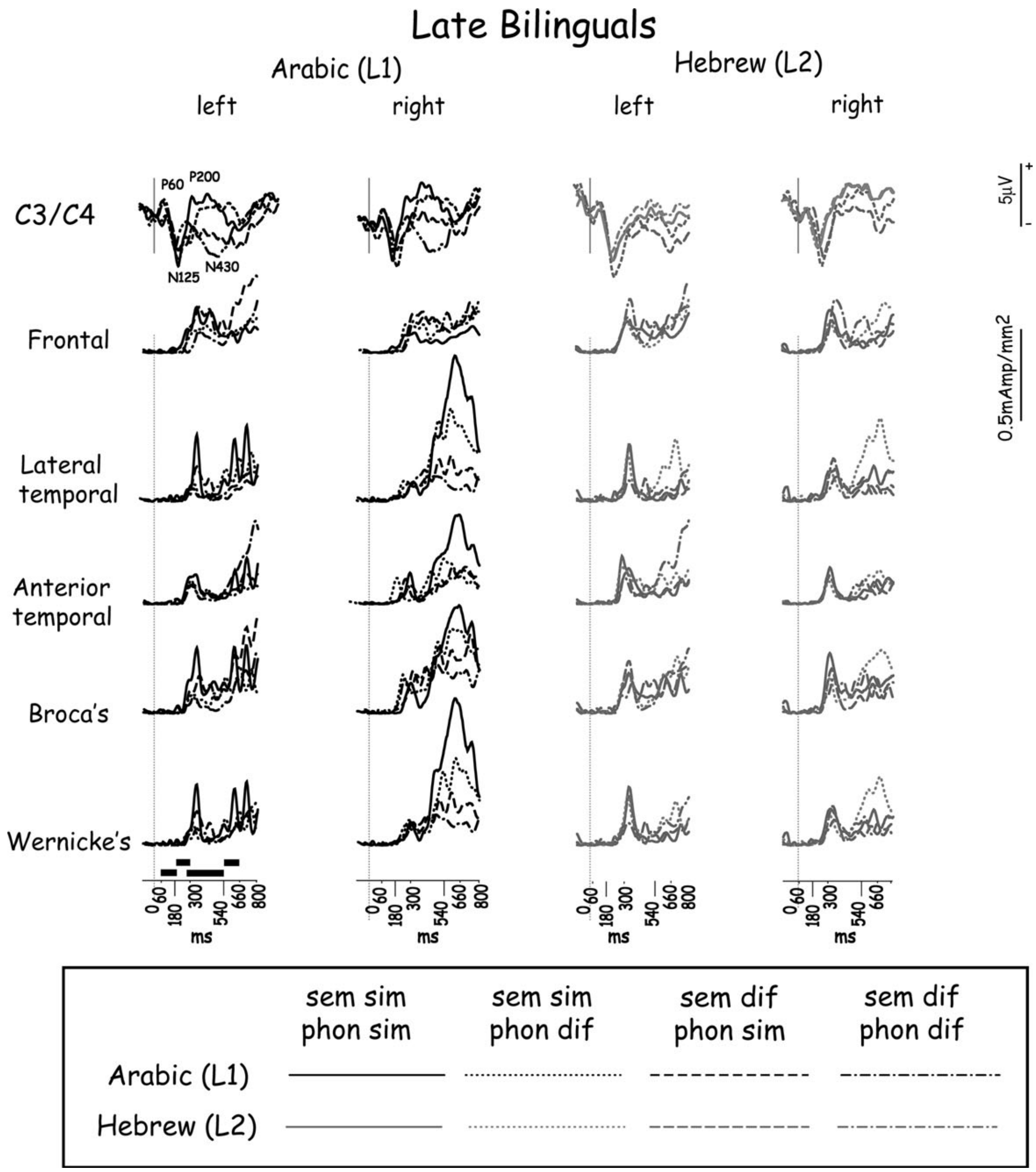

Figure 6.

Scalp potentials (C_3 and C_4, top trace) and estimated source current density time courses at the five brain areas studied in the left and right hemispheres of late bilinguals in response to second words in L1 (Arabic, left column) and L2 (Hebrew, right column) that were semantically (sem) different (dif) and phonologically (phon) similar (sim), semantically similar and phonologically different, semantically and phonologically similar and semantically and phonologically different than the preceding first words in the pair, Vertical dashed lines mark word onset. Bars along the time scale mark the four time periods across which current densities were integrated for the statistical analysis.

General Summary of the Results

Both behavioral and brain activity measures were affected by phonologic and semantic similarities and differences of the second word compared with the preceding first word in the pair. In general, current densities were higher when the second word was different than the preceding first word phonologically, semantically or on both accounts. In addition, interactions of phonologic and semantic similarities with language (L1/L2) and hemisphere (right/left) modulated these effects such that similarity was generally associated with higher early processing activity (priming) in the left hemisphere to L1 words and, with a trend for higher values in late processing with semantic difference (incongruence), also in left hemisphere but more so to L2 words.

DISCUSSION

The following discussion of our results is organized by the hemispheres and brain areas involved in phonologic and semantic processing, continues with language effects and the absence of effects of proficiency, follows with a discussion of processing semantic and phonologic priming and incongruence and ends with conclusion.

Hemispheres and Brain Areas Involved in Phonologic and Semantic Processing

This study showed that activities in the most active brain regions, in right and left hemispheres, that are involved in processing spoken words were different during early (<300 ms) and late (>300 ms) processing and changed with the phonologic and semantic similarity to the preceding word (priming and incongruence). Brain activity across experimental conditions (Figs. 5 and 6) was most prominent in five areas in the right and left hemispheres: (1) frontal/pre-frontal areas (around BA 9, 10, 11, and 47), (2) lateral and inferior temporal lobe (approximately BA 20 and 21), (3) temporal and temporoparietal auditory cortices (the vicinities of BA 40, 41, and 42), (4) around Broca's area (in the vicinity of BA 44) and (5) at Wernicke's area (around BA 22). These five areas have been implicated in language processing based on a variety of lines of evidence. Aphasiology studies have shown Broca's and Wernicke's areas in the left hemisphere to be critical for language output and comprehension [Broca, 1861; Wernicke, 1874], and involvement of additional brain areas in language processing [Hartwigsen et al., 2010; Pulvermuller, 1996; Pulvermuller and Mohr, 1996] was suggested to reflect task effects with a largely bilateral ventral stream which processes speech signals for comprehension, and a left-hemisphere dominant dorsal stream which maps acoustic speech signals to frontal lobe articulatory networks [Hickok and Poeppel, 2007]. Clinical and functional imaging studies showed dominance of the left hemisphere in language processing [Binder et al., 1997; Pujol et al., 1999; Springer et al., 1999; Vikingstad et al., 2000], particularly its frontal and temporoparietal regions, with prelexical speech perception in bilateral superior temporal gyri; meaningful speech in middle and inferior temporal cortex; semantic retrieval in the left angular gyrus and pars orbitalis; and sentence comprehension in bilateral superior temporal sulci [Price, 2010].

Right hemisphere involvement has been reported for a variety of language tasks in clinical and functional imaging studies [Bookheimer, 2002; Buchanan et al., 2000; Chee et al., 2001; Dehaene et al., 1997; Klein et al., 2001; Meyer et al., 2000; Schlosser et al., 1998; Seger et al., 2000; Springer et al., 1999], in behavioral studies [Beeman et al., 2000; Coney and Evans, 2000; Faust and Chiarello, 1998; Faust and Weisper, 2000; Nieto et al., 1999; Sereno, 1999; Weekes et al., 1999; Wuillemin et al., 1994], in lesion studies [Albert et al., 1981; Beeman, 1998; Bookheimer, 2002; Delis et al., 1983; Gold and Kertesz, 2000; Melamed and Zaidel, 1993; Mitchell and Crow, 2005; Morray, 2000; Sabbagh, 1999; Snow, 2000] and in electrophysiological studies [Federmeier and Kutas, 1999; Kiefer et al., 1998; Khateb et al., 2001]. The right hemisphere's role typically involves prosody, melody, emotional expression/perception, and spatial orientation [Martin, 1999; Sabbagh, 1999; Snow, 2000] but also lexical, grammatical, and semantic aspects of language processing [Beeman et al., 2000; Coney and Evans, 2000; Delis et al., 1983; Faust and Chiarello, 1998; Faust and Weisper, 2000; Federmeier and Kutas, 1999; Gold and Kertesz, 2000; Nieto et al., 1999; Sereno, 1999; Seger et al., 2000]. Patients with pure word deafness almost always have bilateral brain damage [Albert et al., 1981], compatible with the right hemisphere's role in phonologic decoding of speech sounds. There are also indications for higher right hemisphere involvement in second language processing [Neville et al., 1997; Wuillemin et al., 1994] but its origins are unclear [Fabbro, 2001b].

In this study, the effects of experimental conditions were observed in both hemispheres, different for left and right hemisphere during early (<300 ms) and late (>300 ms) processing. Right hemisphere activity during early processing in Wernicke's area was diminished by priming (processing phonologically and semantically similar second words), while in the left hemisphere this activity was enhanced by priming. In contrast, during late processing left hemisphere activity in temporal auditory areas and in Wernicke's area was enhanced by incongruence (phonologically and semantically different second words) while no significant effect of incongruence was observed in the right hemisphere. In Broca's area, the most confusing condition—phonologically similar second words that were semantically different—was associated with increased activity on the left while no such effect was observed on the right. These differences in lateralization between early and late processing are in line with earlier suggestions [Pratt et al., 2002; Sinai and Pratt, 2002] of a tiered process consisting of early (<300 ms for bi-syllabic words) phonologic definition of the auditory object (speech/nonspeech, language, accent) and a late (>300 ms for bi-syllabic words) extraction of speech meaning and context. These differences are also in line with magnetoencephalographic evidence of two periods of right hemisphere involvement in reading proficiency of bilinguals [Leonard et al., 2010].

Processing First and Second Language Among Early and Late Bilinguals

There were no language main effects and the involvement of language in interactions with semantic and phonologic similarity did not differ between early and late bilinguals. No consistent differences between L1 and L2 effects were found (Table I) and any language effect may have been overwhelmed by the phonologic and semantic effects discussed in the following section.

The absence of any proficiency (subject group) main effect or involvement in interaction, contrasts with multiple group interactions with setting, hemisphere and language, particularly in response to the first word in the pair, detailed in a companion report (Pratt et al., 2012). Bearing in mind that this study only analyzed brain activity to the second words in the pair, these results are in line with those of the companion study in which the only group effect on processing second words was an interaction of subject group and language in auditory areas during 60–180 ms. The early interaction of proficiency (subject group) and language in second word processing in auditory areas (60–180 ms) in the companion paper, the absence of a proficiency main effect on second word processing in this paper and its prevalence in first word processing in the companion paper may suggest an explanation. We suggest that the first word sets the phonologic and semantic context for processing the second word, which then proceeds within this context. The context set by the first word is verified and updated if necessary at the very onset of second word processing (60–180 ms) according to acoustic cues of the word's language.

Effects of Semantic and Phonologic Priming and Incongruence

The phonologic similarity or difference compared with the preceding first word affected the processing of second words in the pair as well as the behavioral responses to them. The behavioral results show that performance accuracy was lower to phonologically similar words. Thus, in a mixed setting of two phonologically close languages (Hebrew and Arabic) phonologic similarity hinders performance, most probably by requiring ruling out a confusing Stroop-like effect of phonologic similarity despite a semantic difference.

The electrophysiological results found source current densities to vary with the semantic and phonologic nature of the preceding first word, often by interacting with language and hemisphere. These effects include increased current densities during early processing (<300 ms) to phonologically different (phonologic incongruence) and semantically similar (semantic priming) words in auditory areas while in Wernicke's area activity was higher to phonologically and semantically similar words (priming on both accounts). During late processing (>300 ms), all condition which were associated with increased current densities involved processing of semantically different words (incongruence). The latter effect is in line with amplitude of the N_{400} component which is considered a general index of retrieving stored conceptual knowledge associated with a word [Kutas et al., 2011]. Moreover, N_{400} amplitude is dependent on both the stored representation itself, and the retrieval cues provided by the preceding context [Van Petten and Luka, 2006].

Semantic similarity effects as early as 100 ms appear incompatible with models of speech processing, even those that include highly interactive top-down influences. However, top-down models of speech processing such as the TRACE model of speech perception [McClelland and Elman, 1986], posit that identification of phonemes and finding word beginnings can be influenced by lexical information. Furthermore, more recent bottom-up connectionist models of speech recognition, such as Shortlist [Norris, 1994] and Bayesian models such as Shortlist B [Norris and McQueen, 2008], display many of the properties of top down models, including lexical involvement in phonemic decision making. Thus, we propose that the increased current densities to semantically similar second words between 60 and 180 ms is an influence of the first word's semantics on phonologic processing of the second word. Phonologic processing has been shown to take place at 60–150 ms, followed by initial semantic processing at 150–200 ms [Van Petten et al., 1999].

In this study, the early and late effects of priming and incongruence were widespread and consistent, particularly in the brain areas typically associated with speech processing: temporal and temporoparietal auditory areas and Wernicke's area during early and late processing and Broca's area during late processing. Intracranial data [Halgren et al., 1994] found the largest N_{400}-P_{300b} homologues at ventrolateral prefrontal cortex and magnetoencephalography implicated a sequence of activation, beginning in Wernicke's area at 250 ms spreading to anterior temporal sites at 270 ms, to Broca's area by 300 ms, to dorsolateral prefrontal cortices 320 ms and to anterior orbital and frontopolar cortices by 370 ms. This activity was exclusively left-sided until ≈370 ms, and then involved right anterior temporal and orbital cortices [Halgren et al., 2002]. Magnetoencephalography further showed activity spread from the primary sensory areas along the respective ventral processing streams which converged in anterior temporal and inferior prefrontal regions, primarily on the left at around 400 ms [Marinkovic et al., 2003]. Event-related fMRI studies observed more hemodynamic activity for semantically unrelated than related words, and the locations of the hemodynamic effects were left temporal gyrus and left inferior frontal gyrus, compatible with ERP results [Van Petten and Luka, 2006]. All these findings are in line with the results of this study.

A language conflict in reading has been studied in Dutch–English bilinguals using a set of words that exist in both Dutch and English, are spelled and look identically in both languages, but have a different meaning and pronunciation in each language [e.g., "*kind*" van Heuven et al., 2008]. In that study, fMRI located stimulus-based language conflict, as well as differences between monolinguals and bilinguals, to brain regions in the left inferior prefrontal cortex (BA 44, 6) associated with phonologic and semantic processing. A similar effect, but with phonologic rather than orthographic similarity, was confirmed in our results using auditory presentation of words. The effect was particularly evident among late bilinguals in response to L1: SnPM comparisons of current density with L1 second words that were phonologically and semantically similar to the first word, had current densities that were higher than their counterparts in L2. This effect was confirmed in the analysis of variance results from Wernicke's area during 60–180 ms. This priming effect of phonology was overwhelmed in most cases by the effects of semantic incongruence, particularly in late processing. With only a few exceptions, current densities were larger to semantically different second words, particularly at latencies ~400 ms, which are known to be sensitive to semantic incongruence (N_{400}), and in temporal and Broca's areas, known to be involved in speech processing in general, and in language switches in particular [Abutalebi et al., 2008b].

Conclusions

The results of this study show that the distribution of brain activity during speech processing is affected by both phonologic and semantic context (priming and congruence), differently during early (<300 ms) and late (>300 ms) time windows. Early processing in temporal and temporoparietal auditory areas is enhanced by phonologic differences, while in Wernicke's area—by phonologic and semantic similarity between words. In contrast, late processing in temporal areas and in Broca and Wernicke's areas is accompanied by enhanced activity to semantic incongruence between words.

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