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Spatiotemporal Distribution of Cortical Processing of First and Second Languages in Bilinguals. I. Effects of Proficiency and Linguistic Setting

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Abstract: The study determined how spatiotemporal distribution of cortical activity to words in first and second language is affected by language, proficiency, and linguistic setting. Ten early bilinguals and 14 late adult bilinguals listened to pairs of words presented in Arabic (L1), Hebrew (L2), or in mixed pairs and indicated whether both words had the same meaning or not. Source current densities of event-related potentials were estimated. Activity to first words in the pair lateralized to right hemisphere, higher to L1 than L2 during early processing (<300 ms) among both groups but only among late bilinguals during late processing (>300 ms). During early and late processing, activities were larger in mixed than monolinguistic settings among early bilinguals but lower in mixed than in monolinguistic settings among late bilinguals. Late processing in auditory regions was of larger magnitude in left than right hemispheres among both groups. Activity to second words in the pair was larger in mixed than in monolinguistic settings during both early and late processing among both groups. Early processing of second words in auditory regions lateralized to the right among early bilinguals and to the left among late bilinguals, whereas late processing did not differ between groups. Wernicke's area activity during late processing of L2 was larger on the right, while on the left no significant differences between languages were found. The results show that cortical language processing in bilinguals differs between early and late processing and these differences are modulated by linguistic proficiency and setting. *Hum Brain Mapp 34:2863–2881, 2013.*

Key words: event-related potentials; hemispheres; bilingualism; circumstances; fluency

INTRODUCTION

Bilingualism and Proficiency

In its widest sense, the term "bilingual" refers to anyone using two or more languages or dialects in everyday life [Grosjean, 1994]. Neuropsychological studies suggest that bilingual subjects are not "two monolinguistics in one person" and that the interaction of the two languages in the bilingual brain produces a different linguistic entity [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 divided to early and late bilinguals, according to the age

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of second language (L2) acquisition. Early bilinguals are typically similarly 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). Although 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, 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].

Language representation in the brain is influenced by age of acquisition, manner of learning, and language use [Fabbro, 2001b]. A meta-analysis of behavioral studies [Hull and Vaid, 2007] indicated that bilinguals who acquired both languages by age 6 showed bilateral hemispheric involvement for both languages, whereas those who acquired their second language later showed left hemisphere dominance for both languages. Proficiency in L2 similarly affected hemispheric involvement among non-proficient bilinguals, with more left hemisphere dominance than among bilinguals proficient in both L1 and L2. However, as detailed below and in contrast to behavioral and clinical lesion studies, much of the functional imaging literature suggests that early, high proficiency bilinguals are more left lateralized. Interestingly, early bilinguals acquiring a third language (L3) recruit less neural substrate than late bilinguals when using L3, which may indicate that early bilinguals establish an adaptable network to integrate additional languages [Wattendorf, 2001].

Cerebral Representation of Bilingualism

The first language, which is acquired informally, tends to involve both cortical and subcortical structures including basal ganglia and cerebellum (the implicit vs. explicit language hypothesis). When the second language is learned formally and used mainly at school, it tends to be more widely represented in the cerebral cortex than the first language [Fabbro, 2000; Fabbro et al., 1997; Fabbro and Paradis, 1995; Paradis, 1994]. However, if the second language were acquired informally, as often happens in early bilinguals, subcortical structures are also involved, as for first language [Aglioti and Fabbro, 1993; Aglioti et al., 1996; Fabbro, 2000; Fabbro et al., 1997; Fabbro and Paradis, 1995; Paradis, 1994].

A structural imaging study of healthy bilinguals reported a small difference associated with early- compared with late acquisition of L2, and bilingual compared with monolingual experience [Mechelli et al., 2004]. Electrophysiological and functional neuroanatomical studies have defined cortical organization of the two languages in bilinguals as either overlapping or distinct [Fabbro, 2001b]: First and second languages appear to mostly share the same brain regions. Clinical studies of aphasics defined different recovery patterns in multilingual aphasics [Paradis, 1977, 1993, 1998, 2001; Paradis and Canzanella, 1989]. In most bilingual severe aphasics, both languages are affected to the same degree acutely but recovery for L1 and l2 can vary widely [Fabbro, 2001a].

Functional imaging methods, including fMRI and Event-Related Potentials (ERP), indicate that activation by words in L1 and L2 is similarly distributed in the brain [Fabbro, 2001b]. fMRI evidence indicated that while the pattern of brain activity for semantic judgment was largely dependent on proficiency level, age of acquisition (birth or above 6 years old) mainly affected the cortical representation of grammatical processes. These findings indicate that both age of acquisition and proficiency level affect the neural substrates of L2 processing, with a differential effect on grammar and semantics [Wartenburger et al., 2003].

Factors Affecting Spatiotemporal Distribution of Processing L1 and L2

There is disagreement among previous studies on the degree to which first and second language employ overlapping or different brain networks. Electrophysiological evidence supports the involvement of different cortical areas for processing L1 and L2 [Ojemann and Whitaker, 1978; Roux and Tremoulet, 2007; Simos et al., 2001] while fMRI and PET [Abutalebi and Green, 2007; Chee et al., 1999; Hernandez et al., 2000; Klein et al., 1999] support the involvement of overlapping distributions. However, the time course of activity in brain networks involved in L1 and L2 processing has rarely been addressed. Language processing in L1 and L2 among bilingual adults was compared, in the visual modality, combining magnetoencephalography and magnetic resonance imaging [Leonard et al., 2010]. Two time periods that showed differences between L1 and L2 were found with L1 words involving 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. Furthermore, the acquisition of L2 involved early processing in right hemisphere and posterior visual areas that were no longer activated once fluency was achieved.

The distribution of brain processing of language is also modified by the circumstances in which L1 and L2 are used. The few studies that examined the effects of context on language processing among bilinguals [Abutalebi et al 2008a; de Groot et al., 2000; Elston-Guttler et al., 2005a,b; Kerkhofs et al., 2006; Wu and Thierry, 2010] related to reading or picture naming, i.e., visual representations of language, rather than the auditory modality of language—hearing spoken words. Language is primarily an auditory task and it has been shown that processing visual presentation of second language actually activates the auditory, but not the visual, cortex among bilinguals [Wu and

Thierry, 2010]. We will report in this article on the effects of linguistic circumstances on processing auditory presentation of words in L1 and L2.

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 are modified by (1) language proficiency as determined by the degree of bilingualism (early vs. late); and (2) the linguistic setting in which the words are processed (monolinguistic or mixed languages). The effects of semantic and phonologic priming and incongruence on processing L1 and L2 words among early and late bilinguals are reported in a companion report [Pratt et al., 2012].

To address these aims we used auditory presentation, 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 and used the paradigm to define the linguistic setting by presenting both words in the pair in either one language or the other (L1 or L2 monolinguistic settings), or presenting mixed pairs (mixed linguistic setting) throughout the session. The languages used were Hebrew and Arabic, which have similar phonologies, reducing the possible confound of phonologic differences between the two languages.

We analyzed the first and second words in the pair separately because of their different roles in the task—the first word is only memorized while the second word is compared with the memory trace of the first. We hypothesized that right hemisphere activity would be prominent during early phonologic processing, whereas left hemisphere would be prominent during late semantic processing among late bilinguals and a more bilateral pattern in early bilinguals. We expected to find more activity associated with processing L1 and L2 words in the mixed setting than in the monolinguistic settings among both groups. Furthermore, late bilinguals were expected to differ in the distribution of processing L1 and L2, depending on the linguistic setting.

METHODS

A detailed account of the methods is provided in a companion report [Pratt et al., 2012]. The following is a short description of the subjects, stimuli, and procedures, with more details on the analysis that was specific to this study.

Subjects

Twenty-four (10 women and 14 men) 18 to 25 years old right-handed normal hearing 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. All subjects were Israeli Arabs attending a university, who grew up speaking Arabic with relatively high proficiency in Hebrew as well. Ten of the subjects (6 women and 4 men, mean age = 21.2 years, SD = 3.2 years) were defined as Arabic–Hebrew early bilinguals, based on acquisition of both languages before the age of 6 years, and their Arabic/Hebrew COWAT score ratio of 0.8 (SD = 0.2). Fourteen of the subjects (4 women, 10 men, mean age = 20.9 years, SD = 2.0 years) were defined as Arabic-Hebrew late bilinguals, based on acquisition of Hebrew past the age of 8, in the public school system, and their average Arabic/Hebrew COWAT score ratio of 1.4 (SD = 0.3). 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. 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. Based on dictionary entries, the two words in the pair had either the same meaning (synonyms in same-language pairs or translations in mixed language pairs) or different meanings. Probabilities of semantically similar and of semantically different pairs were equal (50%). When the pair consisted of an Arabic word and a Hebrew word (mixed language condition), because of the relative phonologic similarity of Hebrew and Arabic, 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, in the mixed condition pairs consisted of four combinations of semantic and phonologic similarity with equal (25%) probability: semantically and phonologically similar (similar-sounding translation), semantically similar and phonologically different (different-sounding translation), semantically different and phonologically similar (no semantic relation but similar-sounding) and semantically and phonologically different (no semantic relation nor similar sound).

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.

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 deviation 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 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 pressing an appropriate button whether both words in the pair had the same or different meaning, regardless of their language (two alternative forced choice semantic decision).

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/s, filtered (0.1–100 Hz, 6 dB/octave slopes) and stored for offline 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 separately for potentials evoked by the first word and second word in the pair, separately for each language (Arabic and Hebrew) and for each setting (Arabic, Hebrew, or Mixed). In all settings, first word potentials to positive and negative response trials were averaged together because at the time of the first word the nature of the response had not yet been determined, but for second words separate averages were acquired for trials associated with correct positive (semantic congruence) and negative responses (semantic incongruence). Thus, in the monolinguistic settings there were two separate averages for first words in the pair (two languages) and four separate averages (two languages × two response types) for second words in the pair, for each subject. In the mixed condition in which each pair consisted of an Arabic word and a Hebrew word, potentials to first words were averaged separately according to their language (two languages) while second words 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 this study, only second words that were phonologically different than the first word in the pair were analyzed. Thus, in the mixed linguistic condition of this study, there were two first word averages and four separate second word averages (two languages × two semantic similarities). Across all experimental conditions, there were therefore four averages of potentials to first words and eight averages of second words. In all, between 300 and 350 repetitions were averaged to obtain the potentials evoked by each first word and between 130 and 165 trials for second word responses.

After averaging, the data were band-pass 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 used in this study to estimate the distribution of current density in the brain based on the scalp distribution of potentials. In sLORETA, 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]. In this study, sLORETA was applied on the ERP records to image the estimated source current density throughout the duration of the brain potentials recorded in response to each of the four conditions for first words and to each of the eight conditions for the second words, as detailed earlier.

Statistical Analyses

The estimated source current density distributions 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 during which activity was consistently recorded across subjects, words, and experimental conditions.

The task required different processing of the first and second words in the pair. The first word had to be memorized as is to allow its comparison with the following second word, whereas the second word was compared for its meaning (including synonyms) with the meaning of the memorized first word. Furthermore, brain activity in response to first and second words differed in time course and brain regions activated, and brain activity to second words was affected by the nature of the preceding first word in the pair. Therefore, the analyses of findings on first and second words were conducted separately.

Pairwise comparisons of current density distributions

Differences in current density distributions between experimental conditions across all subjects were assessed using Statistical non-Parametric Mapping (SnPM), which 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 using conventional ANOVA results [Laufer and Pratt, 2003; Sinai and Pratt, 2003]. We used the "pseudo-*t*" statistic [Nichols and Holmes, 2002], with an additional 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 experimental conditions using a part-factorial mixed design in which proficiency was a between-subject factor and phonologically similar pairs were not presented in the single language settings and not included in the analysis of the mixed language setting. Specifically, analysis of brain activity in response to the first word and to the second word tested the effects of the following four factors: Subject group (early bilinguals, late bilinguals); Language (Hebrew, Arabic); Hemisphere (left, right); and Linguistic setting (monolinguistic, mixed languages). Analyses of brain activity to second words in the pair were conducted only for words that were phonologically different than the first word (as in the monolinguistic settings), and then, separately for second words that were semantically similar or different compared to the preceding first word. Only effects that were found consistently significant for second words irrespective of semantic similarity to the first word (associated with both positive and negative behavioral responses) were considered significant.

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 $\times$ time, i.e., "area under the curve") during the four time periods following word onset, which were consistently found to be the most active across a number of brain areas. Early processing, which was similar in timing for first and second word included two periods: 60–180 and 180–300 ms (roughly corresponding to P_{60}-N_{125} and P_{200}, respectively); Late processing periods were slightly different for first word (300–420 and 380–660 ms) and second word (260–540 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 later section.

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 found significant.

RESULTS

General Overview

Both reaction time and accuracy measures were affected by language (L1 vs L2). In addition, accuracy was affected by subject group (early vs. late bilinguals) and reaction times by the setting (monolinguistic or mixed). The potentials evoked on the scalp of all subjects in response to first (Fig. 1) and second (Fig. 2) words included a sequence of P_{60}, N_{120}, P_{200}, N_{430}, and P_{600} with similar peak latencies for early and late bilinguals. Source current densities of the scalp recorded potentials were derived (Figs. 3 and 4) and the effects of subject group and experimental conditions on intracranial activities were assessed (Tables I and II) for the five most active brain areas during four time periods defined by the time courses of intracranial activity (Figs. 5 and 6).

The effects of experimental conditions on brain activity are detailed separately for first and second words, and for each word, by time period and brain region. 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 experimental conditions and subject groups. Performance accuracy of the more proficient early bilinguals (82% on average) was significantly higher than among late bilinguals (78% on average) [$F(1, 232) = 4.76$, $P < 0.05$]; L2 (Hebrew) second words were associated with significantly longer reaction times (810 ms on average) than L1 (Arabic) second words (770 ms on average) [$F(1, 232) = 5.23$, $P < 0.03$] and were associated with significantly lower accuracy levels (78% vs. 83%) [$F(1, 232) = 13.95$, $P < 0.0003$]. The mixed linguistic setting required significantly longer reaction times (810 ms on average) than the monolinguistic settings (760 ms on average) [$F(1, 232) = 5.80$, $P < 0.01$]. Although performance accuracy was higher and reaction times shorter among early bilinguals in response to L2, but not L1, these differences between subject groups did not reach significance, and none of the interactions among factors affecting performance reached significance. Overall, accuracy levels (63%–90%) were relatively low considering the simple task that involved elementary school vocabulary. These low levels may reflect subjects' distraction by the laboratory setting, which was uniform across all experimental conditions and therefore unlikely to have affected the effects observed.

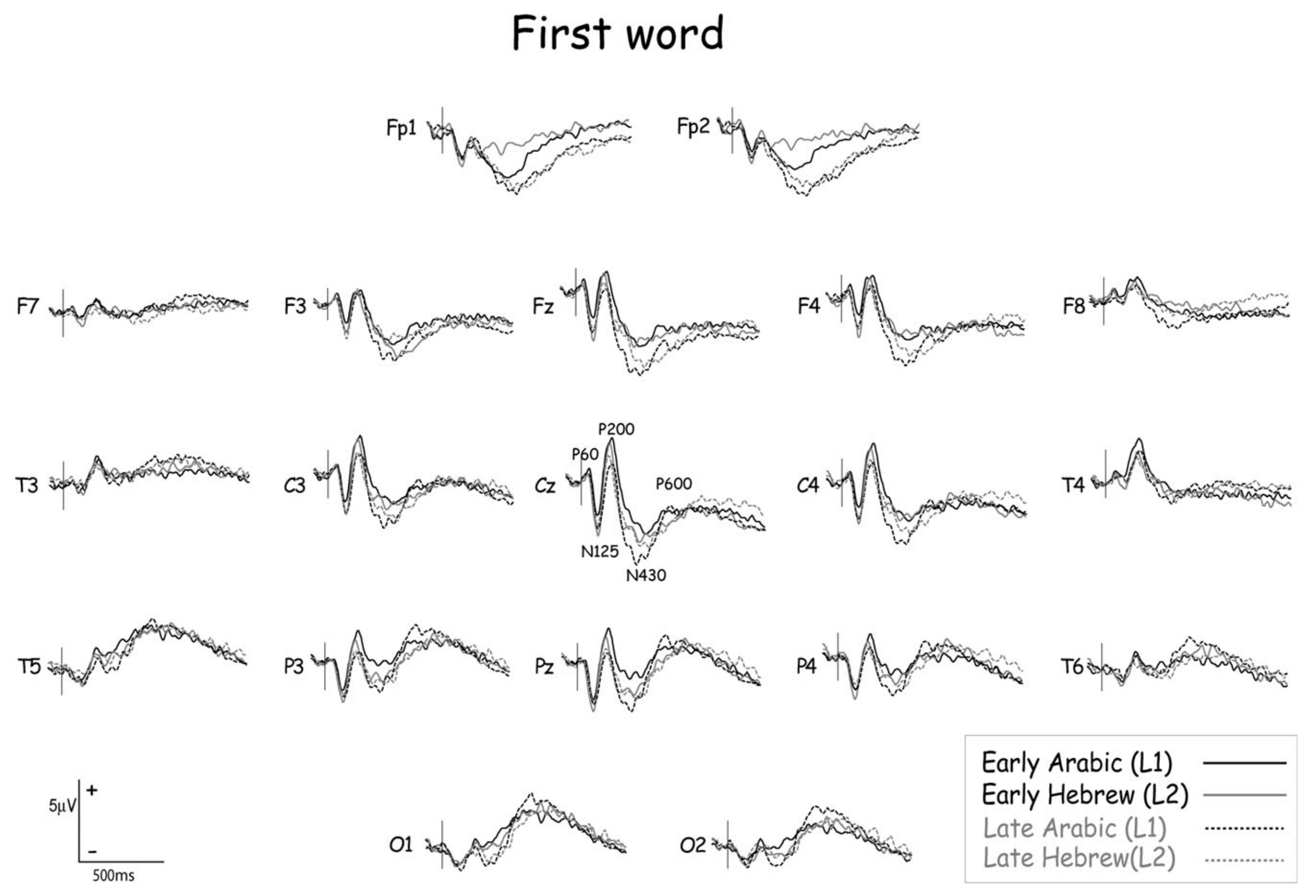

Figure 1.
Potentials to the first words in L1 (Arabic) and L2 (Hebrew), in the respective monolinguistic settings, among early and late bilinguals. The vertical lines close to the beginnings of traces mark the timing of word onset.

Brain Activity to the First Word in the Pair

The results on the effects of proficiency (subject group: early vs. late bilinguals), language (L1-Arabic vs. L2-Hebrew), setting (monolinguistic vs. mixed pairs), and hemisphere (left vs. right cerebral hemisphere) and their interactions are detailed in Table I 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).

During 60–180 ms

Current density in frontal and prefrontal areas (IA), as well as in Broca's area (ID), was significantly higher in the right hemisphere than in the left. In temporal and temporoparietal auditory areas (IC) activity was higher in the monolinguistic settings than in the mixed linguistic setting and a group × hemisphere interaction indicated that activity was higher in the right hemisphere among early bilinguals, while among late bilinguals activity was lateralized to the left hemisphere. A group × setting interaction (ID) indicated that in Broca's area activity was higher in the mixed linguistic setting among early bilinguals, while among late bilinguals it was higher in the monolinguistic settings.

During 180–300 ms

Activity was lateralized to the right in frontal and prefrontal areas (IIA) as well as in Broca's area (IID), and was higher in response to L1 than to L2 in lateral and inferior temporal regions (IIB), temporal and temporoparietal auditory area (IIC), in Broca's area (IID) and in Wernicke's area (IIE). A significant group × setting interaction indicated that in lateral and inferior temporal cortex (IIB), in temporal and temporoparietal auditory cortex (IIC), in Broca's (IID) and in Wernicke's areas (IIE) current densities were higher in the mixed linguistic setting among early bilinguals, while among the late bilinguals they were higher in the monolinguistic settings (Group × Setting interactions). A significant language by setting interaction in lateral and inferior temporal area (IIB), temporal and

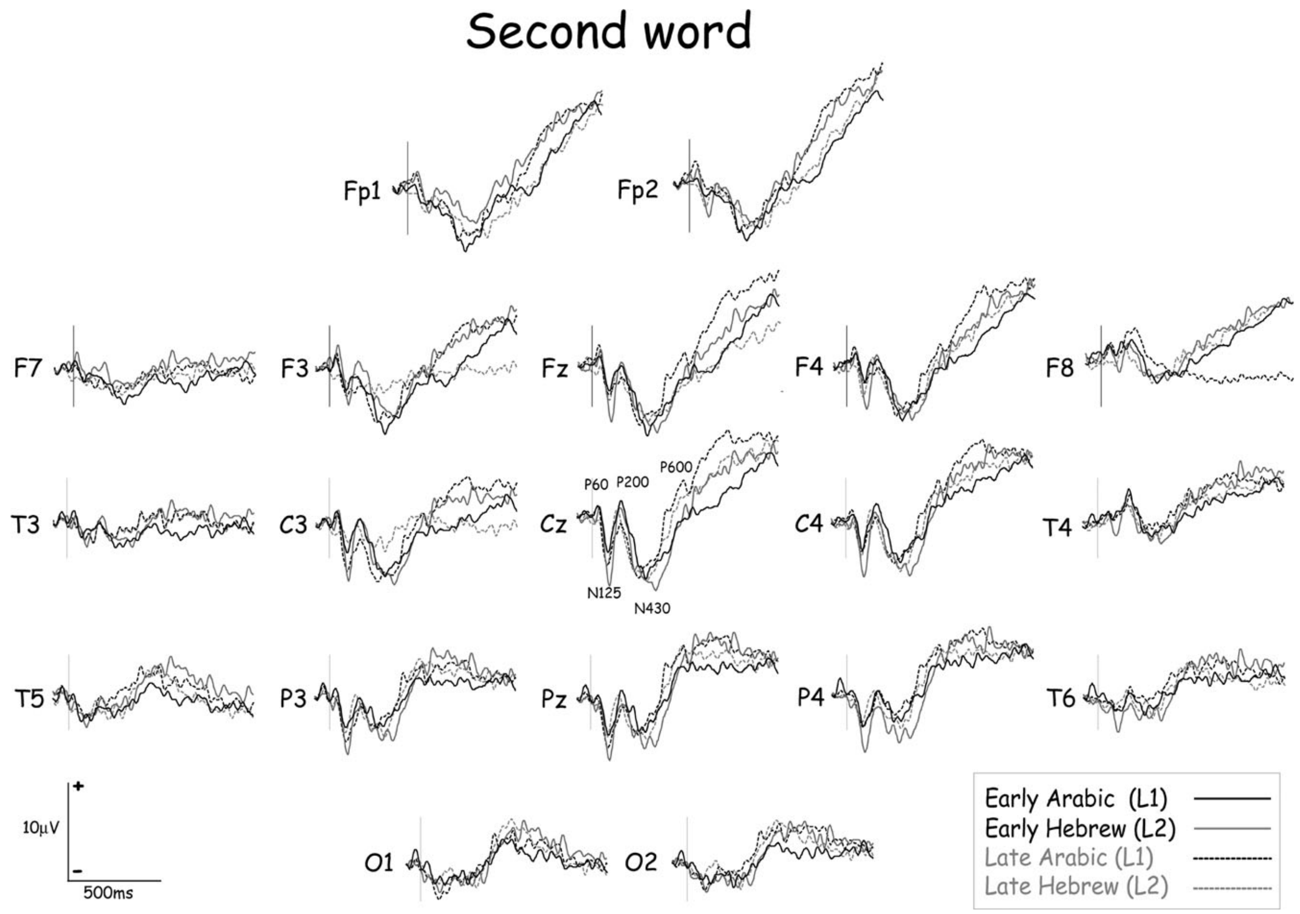

Figure 2.
Potentials to the second words in L1 (Arabic) and L2 (Hebrew), in the respective monolinguistic settings, among early and late bilinguals. The vertical lines close to the beginnings of traces mark the timing of word onset.

temporoparietal auditory cortex (IIC) as well as in Wernicke's area (IIE) indicated that activity was higher in the mixed linguistic setting in response to L2 but not significantly different between settings in response to L1. A significant hemisphere × setting interaction (IIC) indicated higher current densities in the right hemisphere's temporal and temporoparietal auditory cortex in the mixed linguistic setting than in the monolinguistic settings, whereas in the left hemisphere the trend was reversed with higher values in the monolinguistic settings than in the mixed setting.

During 300–420 ms

Current densities were higher to L1 than to L2 in temporal and temporoparietal auditory areas (IIIC), in Broca's area (IIID) and in Wernicke's area (IIIE), and a significant group by language interaction in Broca's area (IIID) indicated higher values to L1 than L2 among late bilinguals and approximately equal values among early bilinguals. A group × setting interaction in each of the five brain areas (IIIA–IIIE) indicated that current densities were higher in the mixed than in the monolinguistic setting among early bilinguals, and the reverse was true among late bilinguals. The interaction of hemisphere and setting (IIIC and IIID) indicated that in temporal and temporoparietal auditory areas as well as in Broca's area activity in the right hemisphere was higher in the mixed than in the monolinguistic settings, whereas in the left hemisphere the reverse was true.

During 380–660 ms

Temporal and temporoparietal auditory areas (IVC) had higher current densities to L1 than to L2 and in the right than in the left hemisphere. A significant group × setting interaction (IVA) indicated that among early bilinguals current densities in Frontal and Prefrontal areas were higher in the mixed than in the monolinguistic setting whereas among late bilinguals the reverse was true. A significant interaction of hemisphere and setting (IVD) indicated that in Broca's area activity in the right hemisphere

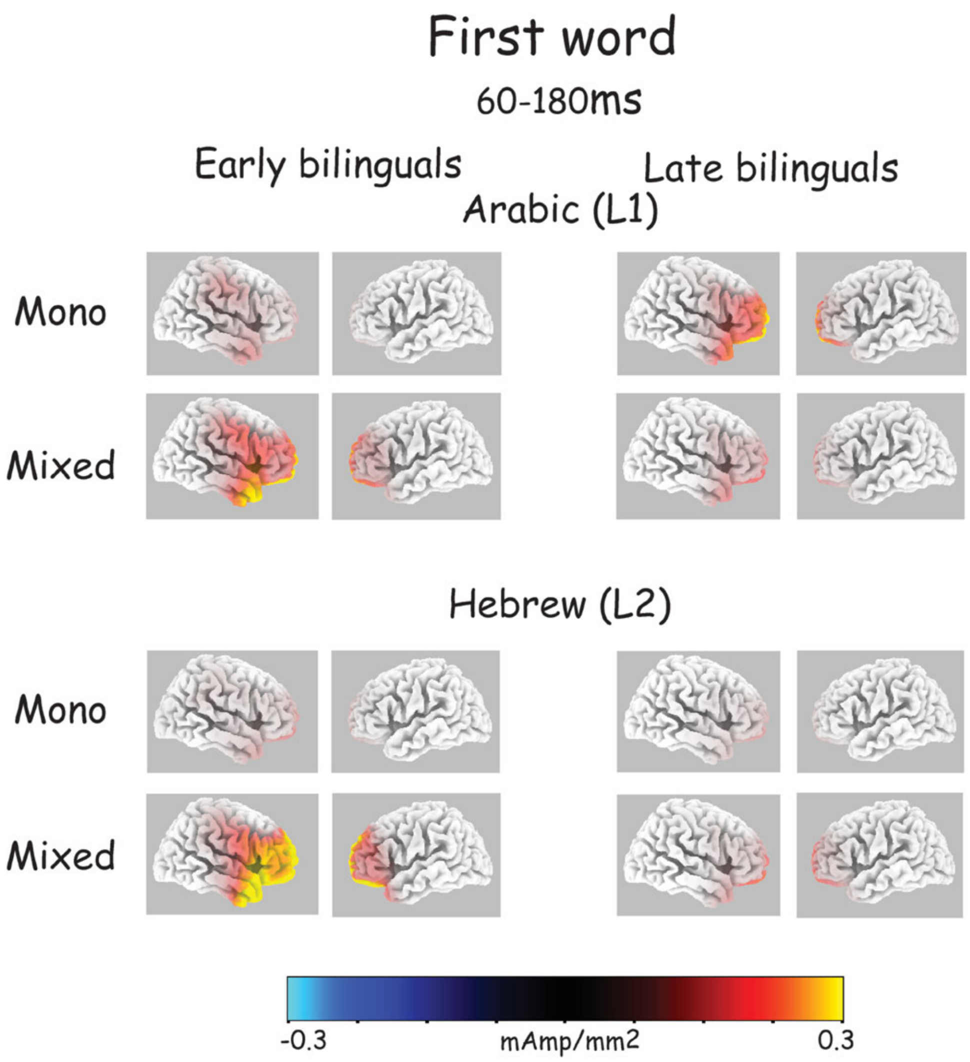

Figure 3.

Source current density distributions during 60–180 ms, in response to the first words in L1 (Arabic) and L2 (Hebrew), in the respective monolinguistic settings and in the mixed setting, among early and late bilinguals (during N_{125} in Fig. 1). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

was higher in the mixed than in the monolinguistic settings, whereas in the left hemisphere activity was higher in the monolinguistic settings.

SnPM comparisons of current density distributions in response to first words in the pair among late bilinguals found that in the mixed language setting L1 involved more late (>300 ms) right hemisphere parietal activity than L2, whereas early bilinguals showed no significant differences in distribution between languages nor among settings. In addition, current densities among late bilinguals were higher in the right temporoparietal and frontal regions during early (<300 ms) processing and in frontal and prefrontal areas to L2 words in the L2 setting during late (>300 ms) processing.

Brain Activity to the Second Word in the Pair

In addition to the effects of subject group (early vs. late bilinguals), language (L1-Arabic vs. L2-Hebrew), setting (monolinguistic vs. mixed word pairs), and hemisphere (left vs. right cerebral hemisphere) source current densities in response to second words in the pair were affected by the preceding first word's phonologic similarity (same vs. different) and semantic meaning (same vs. different), as detailed in the companion report [Pratt et al., 2012). In this study, only second words that were phonologically different than the preceding first word were presented in the monolinguistic settings (avoiding repetition) and in the mixed linguistic setting they were the only ones analyzed.

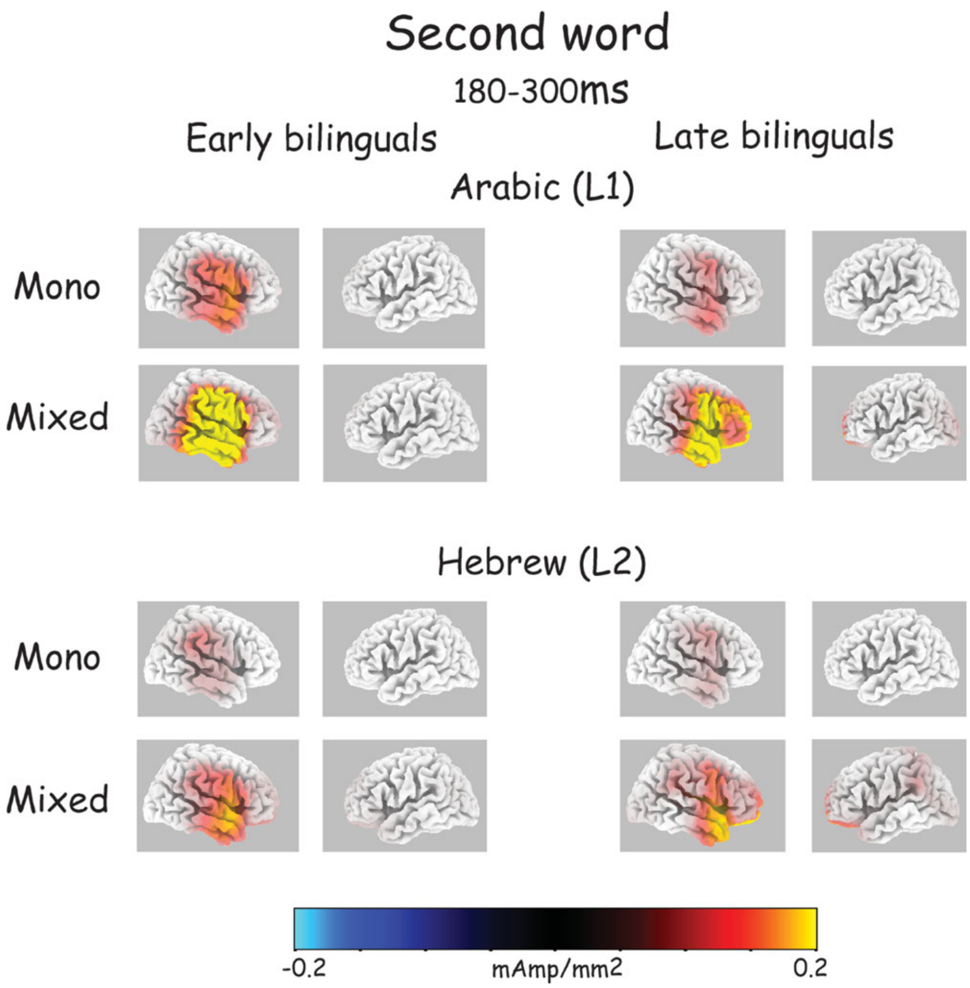

Figure 4.

Source current density distributions during 180–300 ms, in response to the second words in L1 (Arabic) and L2 (Hebrew) and in the mixed linguistic settings, that were semantically and phonologically different than the first word preceding them (during P_{200} in Fig. 2). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

To negate the effects of semantic similarity/difference compared with the first word, only effects that were consistently significant across semantic similarity and difference were considered significant. The results are detailed in Table II 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). Comparing Tables I and II note the striking difference between first and second words in the number and distributions of significant effects: no significant effects were observed in the frontal and prefrontal areas in response to the second word and overall the number of significant effects in the other areas was much smaller than to the first word in the pair.

During 60–180 ms

Current densities in temporal and temporoparietal auditory areas (IC) were affected by an interaction of group and hemisphere which resulted in higher values on the right among early bilinguals and higher values in the left hemisphere among late bilinguals.

During 180–300 ms

Higher current densities were associated with the mixed setting compared with the monolinguistic settings in all areas except frontal and prefrontal cortex (IIB-IIIE). Activity was also higher in the left hemisphere than in the right hemisphere in the lateral and inferior auditory areas (IB) as well as in Broca's (IID) and in Wernicke's areas (IIE). In

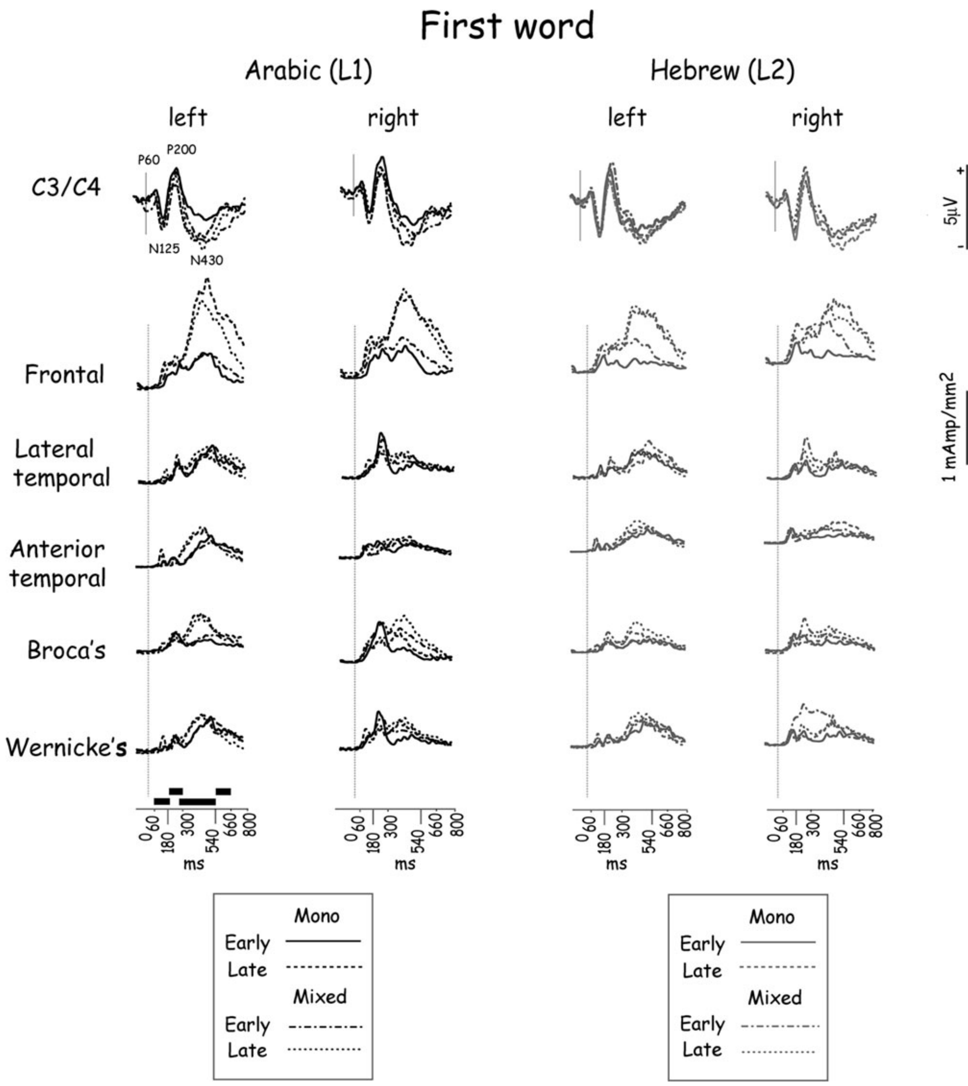

Figure 5.
Scalp potentials (C_3 and C_4, top row) and estimated source current density time courses at the five brain areas studied in the left and right hemispheres of early and late bilinguals in response to first words in L1 (Arabic, left two columns) and L2 (Hebrew, right two columns) in the three linguistic settings. 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.

Broca's area higher current densities were noted to L1 than to L2 (IID). Lateral and inferior temporal areas also showed a language × hemisphere interaction (IIB), which indicated higher values to L1 than L2 in the right hemisphere and approximately similar values to L1 and L2 in the left hemisphere.

During 260–540 ms

Higher current densities were found in the mixed setting compared with the monolinguistic setting in temporal and temporoparietal auditory areas (IIIC), in Broca's area (IIID) and in Wernicke's area (IIIE). A significant language × hemisphere interaction in Wernicke's area (IIIE) indicated higher current densities to L2 than to L1 in the right hemisphere, whereas in the left hemisphere values were similar.

During 540–660 ms

Temporal and temporoparietal auditory areas (IVC) had higher current densities in the mixed setting than in the monolinguistic settings. SnPM comparisons of current density distributions among early and late bilinguals to

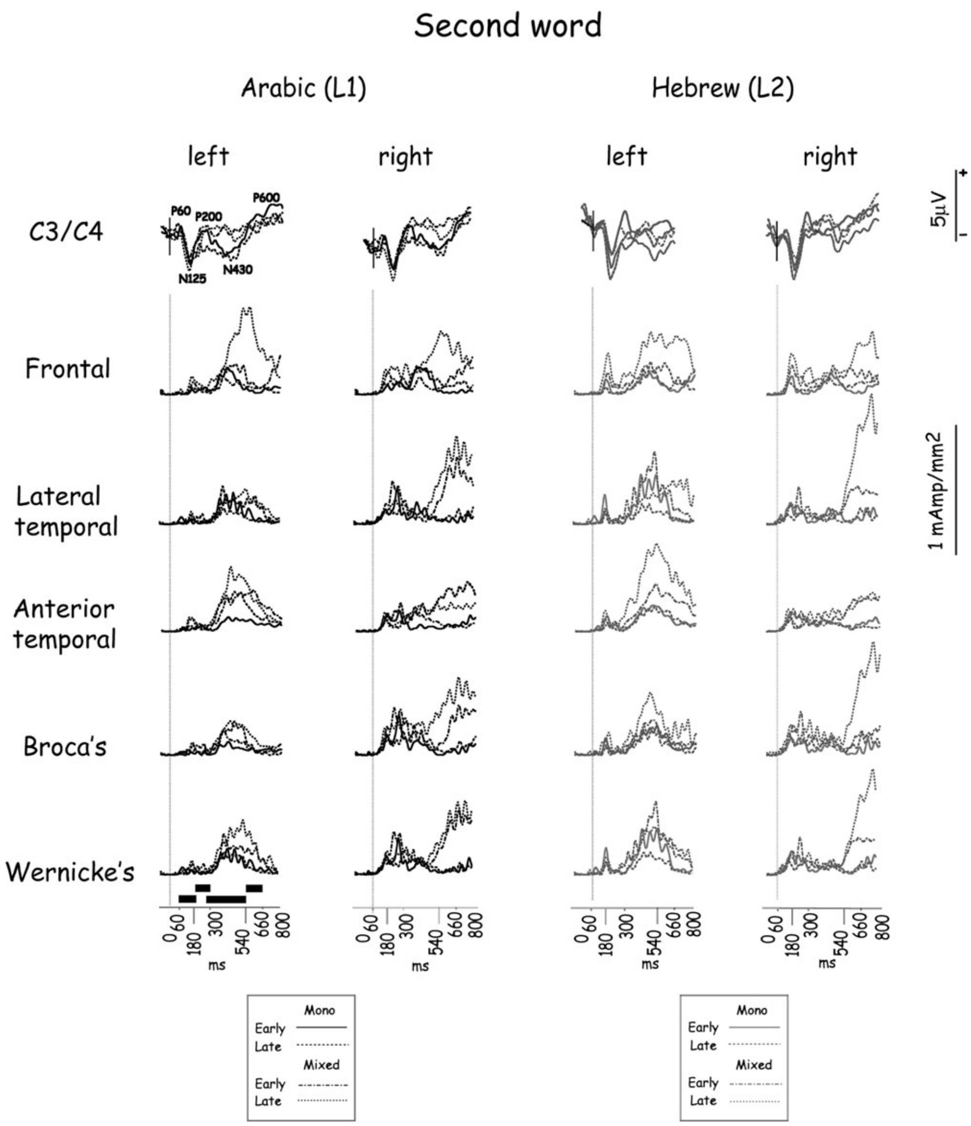

Figure 6.

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 early and late bilinguals in response to second words in L1 (Arabic, left column) and L2 (Hebrew, right column) that were 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.

second words in the pair found few differences across experimental conditions and between groups. During 260–540 ms significantly higher current densities were found among late bilinguals in right lateral and inferior temporal areas and higher values in right temporal and temporoparietal auditory areas among early bilinguals.

General Summary of the Results

Behavioral results were affected by proficiency (early vs. late bilinguals), language and setting, with better performance by the more proficient group, in responding to L1 and in the monolinguistic settings. Early (<300 ms) processing of the first word in the pair was overall more prominent in the right hemisphere frontal and Broca's areas than in the respective left hemisphere areas and to L1 than to L2 in all but the frontal regions. It was more prominent in the mixed than in the monolinguistic setting among early bilinguals, whereas among late bilinguals it was more prominent in monolinguistic than in the mixed setting in temporal, Broca's and Wernicke's areas. In auditory areas, activity was also higher in the mixed setting in the

TABLE I. First words in the pair: significant effects (in Italics) of subject group (Group: early vs late bilinguals), language (Lang: L1-Arabic vs L2-Hebrew), hemisphere (Hem: Left vs. right cerebral hemisphere) and setting (Set: monolinguistic vs mixed pairs) on current densities during four time periods in five brain areas

	I (60–180 ms)	II (180–300 ms)	III (300–420 ms)	IV (380–660 ms)
A: Frontal/prefrontal (BA 9, 10, 11, and 47)	*Rt > Lt* ($F = 5.78$, $P < 0.03$)	*Rt > Lt* ($F = 4.76$, $P < 0.05$)	*Group × Set*[a] ($F = 5.35$, $P < 0.04$)	*Group × Set*[a] ($F = 6.21$, $P < 0.03$)
B Lateral/inferior temporal (BA 20, 21)		*L1 > L2* ($F = 12.99$, $P < 0.002$) *Group × Set*[a] ($F = 10.69$, $P < 0.005$) *Lang × Set*[b] ($F = 5.32$, $P < 0.04$)	*Group × Set*[a] ($F = 4.72$, $P < 0.05$)	
C: Temporal/temporoparietal auditory (BA 40, 41 and 42)	*Mono > Mix* ($F = 4.94$, $P < 0.04$)	*L1 > L2* ($F = 8.17$, $P < 0.02$) *Lang × Set*[b] ($F = 4.79$, $P < 0.05$)	*L1 > L2* ($F = 7.77$, $P < 0.02$)	*L1 > L2* ($F = 6.11$, $P < 0.03$)
	Group × Hem[c] ($F = 6.47$, $P < 0.02$)	*Group × Set*[a] ($F = 6.60$, $P < 0.02$) *Hem × Set*[d] ($F = 5.38$, $P < 0.04$)	*Group × Set*[a] ($F = 4.41$, $P < 0.05$) *Hem × Set*[d] ($F = 5.63$, $P < 0.03$)	*Lt > Rt* ($F = 6.20$, $P < 0.03$)
D: Broca's (BA 44)	*Rt > Lt* ($F = 7.51$, $P < 0.02$)	*L1 > L2* ($F = 6.87$, $P < 0.02$)	*L1 > L2* ($F = 6.42$, $P < 0.03$) *Group × Lang*[e] ($F = 4.42$, $P < 0.05$)	*Hem × Set*[d] ($F = 5.22$, $P < 0.04$)
	Group × Set[a] ($F = 8.10$, $P < 0.02$)	*Rt > Lt* ($F = 4.93$, $P < 0.04$) *Group × Set*[a] ($F = 11.57$, $P < 0.003$)	*Group × Set*[a] ($F = 6.98$, $P < 0.02$) *Hem × Set*[d] ($F = 10.31$, $P < 0.005$)	
E: Wernicke's (BA 22)		*L1 > L2* ($F = 11.73$, $P < 0.003$) *Lang × Set*[b] ($F = 4.41$, $P < 0.05$) *Group × Set*[a] ($F = 12.10$, $P < 0.003$)	*L1 > L2* ($F = 7.78$, $P < 0.02$) *Group × Set*[a] ($F = 6.60$, $P < 0.02$)	

All F values had (1, 19) degrees of freedom. *Rt*, for Right; *Lt*, for Left; *Mono*, Monolinguistic; and *Mix* represents Mixed setting. The significant interactions are detailed by footnotes.
[a]Mix > Mono in Early bilinguals, Mono > Mix in Late bilinguals.
[b]Mix > Mono in L2, Mix ≈ Mono in L1.
[c]Rt > Lt in early bilinguals, Lt > Rt in Late bilinguals.
[d]Mix > Mono in Rt, Mono > Mix in Lt.
[e]L1 > L2 in Late bilinguals, L1 ≈ L2 in Early bilinguals.

right hemisphere and in the monolinguistic settings—in the left hemisphere. Overall, early activity to L1 was more prominent than to L2 among late bilinguals while among early bilinguals there were no significant differences between activity to L1 and L2.

Late (>300 ms) processing of the first word was also more prominent to L1 than to L2 in auditory areas, in Broca's area and in Wernicke's area. In auditory areas, late processing was more prominent in the left than in the right hemisphere. In Broca's area, activity to L1 was more prominent than to L2 among late bilinguals, whereas among late bilinguals there was no significant difference between languages. In all brain areas, late processing was more prominent in the mixed than in the monolinguistic setting among early bilinguals, whereas among late bilinguals it was more prominent in monolinguistic than in the mixed setting. In auditory areas and in Broca's area, activity was also more prominent in the right hemisphere in the mixed setting and in the left hemisphere in the monolinguistic settings.

In contrast to the many significant effects of subject groups and experimental conditions on processing the first word in the pair, second word processing was much less affected by experimental conditions. Early (<300 ms) processing in all but the frontal areas involved higher current densities in the mixed than in the monolinguistic setting. In auditory areas higher values were noted on the right among early bilinguals and on the left among late bilinguals. In the right hemisphere, lateral and inferior temporal areas processing L1 was more prominent than L2 while

TABLE II. Second words in the pair: significant effects (in *Italics*) of subject group (*Group:* early vs. late bilinguals), language (*Lang:* L1-Arabic vs. L2-Hebrew), hemisphere (*Hem:* Left vs. right cerebral hemisphere), and setting (*Set:* monolinguistic vs. mixed pairs) on current densities 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)		*Mix > Mono* ($F = 7.59$, $P < 0.02$) *Rt>Lt* ($F = 13.80$, $P < 0.002$) *Lang × Hem*[a] ($F = 7.61$, $P < 0.02$)		
C: Temporal/temporoparietal auditory (BA 40, 41, and 42)	*Group × Hem*[b] ($F = 6.26$, $P < 0.03$)	*Mix > Mono* ($F = 15.79$, $P < 0.001$)	*Mix > Mono* ($F = 19.47$, $P < 0.001$)	*Mix > Mono* ($F = 20.22$, $P < 0.001$)
D: Broca's (BA 44)		*Mix > Mono* ($F = 9.99$, $P < 0.006$) *Rt > Lt* ($F = 15.10$, $P < 0.001$) *L1 > L2* ($F = 8.23$, $P < 0.01$)	*Mix > Mono* ($F = 12.07$, $P < 0.003$)	
E: Wernicke's (BA 22)		*Mix > Mono* ($F = 11.16$, $P < 0.004$) *Rt > Lt* ($F = 12.57$, $P < 0.003$)	*Mix > Mono* ($F = 12.45$, $P < 0.003$) *Lang × Hem*[c] ($F = 9.31$, $P < 0.007$)	

All F values had (1, 19) degrees of freedom. *Rt*, Right; *Lt*, Left; *Mono*, Monolinguistic; *Mix*, Mixed setting. The significant interactions are detailed by footnotes.
[a]L1 > L2 in Rt hemisphere, L1 ≈ L2 in Lt hemisphere.
[b]Rt > Lt in Early bilinguals, Lt > Rt in Late bilinguals.
[c]L2 > L1 in Rt hemisphere, L1 ≈ L2 in Lt hemisphere.

in the left hemisphere no significant differences between L1 and L2 were found. Late (>300 ms) processing of the second word in the pair was more prominent in the mixed setting than in the monolinguistic settings in auditory areas and in Broca's and Wernicke's areas. In Wernicke's area, processing L2 was more prominent in the right hemisphere while in the left hemisphere no significant differences between L1 and L2 were found. No other significant effects were found for second word processing.

DISCUSSION

The following discussion of our results is organized by the hemispheres and brain areas involved in language processing, continues with the effects of proficiency and linguistic setting, follows with a discussion of the relation of the results to memory processes, and ends with conclusions.

Hemispheres and Brain Areas Involved in Language Processing

This study showed that cortical activity to first words in pairs of phonologically different words was higher in the right hemisphere regardless of L2 proficiency during early processing (<300 ms), but only among late bilinguals during late processing (>300 ms). Late processing of first words in auditory cortical regions involved larger activity in left than right hemisphere regardless of proficiency. Early processing of second words in auditory regions lateralized to the right among early bilinguals and to the left among late bilinguals. Wernicke's area activity during late processing of L2 second words was larger in the right hemisphere whereas in the left hemisphere no significant differences between L1 and L2 were found.

Neural mechanisms underlying language processing were historically localized to the left frontal lobe for speech production [Broca, 1861] and to the left temporoparietal region for language comprehension [Wernicke, 1874]. More recent neuroimaging studies confirmed the importance of Broca's and Wernicke's areas for language processing, but suggested that they were part of a wider network including multiple supplementary areas [Pulvermuller, 1996], perisylvian areas in the left hemisphere and other areas in both hemispheres, reflecting specific features of speech [Hartwigsen et al., 2010; Pulvermuller and Mohr, 1996]. The variability in the areas reportedly involved in speech processing was suggested to reflect task effects on speech-related processing systems: a largely bilateral ventral stream, which processes speech signals for comprehension, and a strongly left-hemisphere dominant dorsal stream which maps acoustic speech signals to frontal lobe articulatory networks [Hickok and Poeppel, 2007].

A review of fMRI studies suggested localization of 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].

In this study, brain activity across experimental conditions (Figs. 3 and 4) was most prominent in five areas: (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 other 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, respectively [Broca, 1861; Wernicke, 1874]. More recent studies, using clinical and functional imaging evidence, 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] and crucial involvement of its frontal and temporoparietal regions in fundamental language processes. However, more recent neuroimaging studies on complex language inputs (e.g., narratives) indicated additional involvement of right hemisphere anterior temporal homologues of left hemisphere language areas [Bookheimer, 2002; Humphries et al., 2001; Xu et al., 2005]. In addition, clinical studies of aphasia found that language comprehension in patients with right hemisphere damage was also affected [Beeman, 1998; Bookheimer, 2002]. Additional evidence for right hemisphere involvement has also been reported for a variety of language tasks in 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], 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], lesion studies [Albert et al., 1981; Delis et al., 1983; Gold and Kertesz, 2000; Melamed and Zaidel, 1993; Morray, 2000; Sabbagh, 1999; Snow, 2000], and electrophysiological studies [Federmeier and Kutas, 1999; Khateb et al., 2001; Kiefer et al., 1998], drawing attention to the right hemisphere's importance in clinical assessments of language functions [Mitchell and Crow, 2005]. The right hemisphere's role involves not only prosody, melody, emotional expression/perception, and spatial orientation [Martin, 1999; Sabbagh, 1999; Snow, 2000] but also lexical, grammatical and semantic aspects of language [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 who suffer from pure word deafness almost always have bilateral brain damage [Albert et al., 1981], indicating a crucial role for the right hemisphere in phonologic decoding of speech sounds.

There are indications for more right hemisphere involvement in second language processing [Neville et al., 1997; Wuillemin et al., 1994] but its origins are unclear [Fabbro, 2001b]. The results of this study, using the high temporal resolution of electrophysiological functional imaging, may therefore help to resolve some of the disagreements on the roles of the two hemispheres and their subunits in language processing.

In this study, distribution of speech processing varied between early and late bilinguals and between L1 and L2, involving both hemispheres. Early ($<$300 ms) processing of first and second words involved right hemisphere prominence among early bilinguals and some left hemisphere prominence among late bilinguals, whereas late processing ($>$300 ms) was mostly left hemisphere prominent. These findings are in line with earlier suggestions [Pratt et al., 2002; Sinai and Pratt, 2002] of a tiered process consisting of early ($<$300 ms for bisyllabic words) phonologic definition of the auditory object (speech/non-speech, accent) and a late ($>$300 ms for bisyllabic words) extraction of speech meaning and context. The findings on early right hemisphere processing of language material are also in line with magnetoencephalographic evidence of two periods of right hemisphere involvement in reading proficiency of bilinguals [Leonard et al., 2010]: L1 words evoked a typical left-lateralized sequence of activity, first in ventral occipitotemporal cortex, previously associated with visual word-form encoding, and then ventral frontotemporal regions associated with lexico-semantic processing. In contrast, words in L2 activated right ventral occipitotemporal cortex more strongly from $\sim$135 ms, and this activation was attenuated when words became familiar with repetition. At $\sim$400 ms, L2 responses were generally later than L1, more bilateral, and included the same lateral occipitotemporal areas as were activated by pictures. The study also showed that the acquisition of L2 involves early processing in right hemisphere and posterior visual areas that are not activated once fluency is achieved.

Early bilinguals in this study involved more early right hemisphere activity, suggesting that they invest in early phonologic processing of the words more than late bilinguals, in line with the acoustic hypothesis of right hemisphere sound processing [Wong, 2002] involving phonology. This may echo the simultaneous acquisition of L1 and L2 by early bilinguals, requiring them to first differentiate which language is heard, based on subtle phonologic cues, and then proceeding with the networks that are appropriate for the language. The early involvement of the right hemisphere in language processing may have been overwhelmed by the involvement of the left hemisphere in later processing. Furthermore, the brief duration of right hemisphere involvement may have been missed by the low temporal resolution of some of the methods used.

Late and Early Bilinguals

The results of this study showed right hemisphere prominence of late (>300 ms) processing of first words in the pair only among late bilinguals. During both early and late processing of first words, cortical activities were larger in mixed than monolinguistic settings among early bilinguals whereas among late bilinguals activity was lower in mixed than in monolinguistic settings. Second word early processing in auditory regions lateralized to the right among early bilinguals and to the left among late bilinguals.

There is disagreement on the distribution of cortical processing of L1 and L2 in bilinguals. The cortical distribution has been described as either overlapping or distinct [Abutalebi and Green, 2007; Fabbro, 2001b; Ojemann and Whitaker, 1978; Simos et al., 2001]. Evidence from neuroimaging studies supports a similar cerebral activation by L1 and L2 lexicons in both early and late bilinguals [Chee et al., 1999; Hernandez et al., 2000; Illes et al., 1999; Klein et al., 1999]. This similarity applies only to words, while the representation of grammatical aspects of languages differs between the two languages if L2 is acquired after the age of 7. In addition, representation of grammatical aspects [Kim et al., 1997; Neville et al., 1992, 1997; Weber-Fox and Neville, 1997], and verbal working memory [Xue et al., 2004] of L2 differs when automatic processing and accuracy are lower than with the native language. Furthermore, a meta-analysis of hemodynamic studies indicated stronger activation during L2 processing for task-specific subgroups of L2 speakers in some, but not all brain regions that are typically activated in L1 processing [Indefrey, 2006].

Functional magnetic resonance comparison of Spanish-English bilinguals with English monolinguals suggested that bilinguals (presumably late bilinguals) had a significantly greater increase in the blood oxygenation level-dependent (BOLD) signal in the left inferior frontal cortex (BA 45) when processing L1 than monolinguals [Kovelman et al., 2008]. Fine-grained analysis of magnetoencephalography (MEG) to words found subtle differences between different languages in the bilingual brain, particularly in the left temporal lobe [Simos et al., 2001]. Electrocortical stimulation of the temporal lobe in bilingual patients undergoing surgery [Ojemann and Whitaker, 1978] showed that while L1 and L2 shared some common areas, they also involved independent brain regions. Moreover, whereas stimulation of some brain areas of epileptic patients interfered with both L1 and L2 picture naming, stimulation of other areas disturbed L1 but not L2 naming and vice versa [Lucas et al., 2004]. In another cortical electrostimulation study, bilingual patients not only had common but also different cortical areas for L1 and L2 in temporoparietal and frontal areas [Roux and Tremoulet, 2007]. In contrast, others argue that acquiring L2, whether early or late, involves the same network as L1 [Abutalebi and Green, 2007], and that neuroimaging evidence of more extensive left prefrontal activation by L2 may be attributed to its conscious non-automatic processing.

In our results, similar to earlier fMRI studies on bilinguals [e.g., Kovelman et al., 2008] in monolinguistic settings, Broca's area and the adjacent frontal/prefrontal regions showed increased activation at approximately 400 ms for late bilinguals tested in the monolinguistic settings (Figs. 5 and 6). This increase, compared with early bilinguals in our study, is also in agreement with a report on reduced frontal activation with increasing L2 proficiency [Stein et al., 2009]. The high temporal resolution of this study shows that the distribution of speech and language processing between hemispheres and among brain regions in each hemisphere are sensitive to the subject's proficiency in the language but also to the linguistic setting in which words are presented (discussed in later section).

Our results point to brain areas in which activity differentiated late and early bilinguals. In response to first words in the pair differences between subject groups had wide spread higher current densities among early bilinguals in the mixed setting, but higher values in the monolinguistic settings among late bilinguals. In addition, higher values were found in Broca's area to words in L1 (Arabic) and in the monolinguistic settings among late bilinguals, in contrast to early bilinguals who showed no language effect and higher values in the mixed setting. In response to the second word in the pair, the only proficiency effect was higher current density in temporal and temporoparietal auditory areas on the right among early bilinguals and on the left among late bilinguals. Early bilinguals were otherwise less affected by experimental conditions with fewer hemispheric differences compared with late bilinguals.

The finding that late bilinguals had more left hemisphere late activity to L1 than to L2 under similar conditions is in line with primarily left hemisphere processing of L1. This is in contrast to early bilinguals that showed no such differences between L1 and L2, compatible with their simultaneous acquisition and similar cerebral distribution of processing L1 and L2. Moreover, current density distributions among early bilinguals tended to be less lateralized, in line with behavioral [Hull and Vaid, 2007] and fMRI [Marangolo et al., 2009] evidence. All these findings may be explained by early bilinguals acquiring both languages in parallel, involving the same neuronal infrastructure in both hemispheres.

Linguistic Setting

The behavioral results of this study showed that the mixed linguistic setting required significantly longer reaction times than the monolinguistic settings. This effect of settings was also evident in higher current densities in both early and late processing of first words in the mixed pairs among early bilinguals and in the monolinguistic settings among late bilinguals. In processing the second word, current densities were consistently higher in the mixed setting, regardless of proficiency.

These trends are in line with the mixed linguistic setting's more confusing circumstances, requiring investment of more processing resources. This interpretation is in line with earlier reports showing that switching to the less-exposed language (L2) involves selective engagement of the anterior cingulate cortex, putatively involved in cognitive and executive control [Abutalebi et al., 2008b]. Our SnPM results replicate this finding with higher current densities in frontal and prefrontal areas among late bilinguals during late processing of first words in the L2 setting. Second word in the pair was also associated with higher values in prefrontal areas among late bilinguals in the mixed setting (Fig. 4) but this group × setting interaction did not reach significance. This suggests that late bilinguals switching languages or processing a less-familiar language engage more controlled processing resources than early bilinguals who are equally adept at processing both languages in any setting.

Semantic Memorization and Retrieval

Differential recovery of first and second languages following brain lesions has been attributed to different cerebral representations for the two languages [e.g. Albert and Obler, 1978) as well as to different pathophysiological changes of networks subserving language [Fabbro, 1999; Paradis 1998]. For instance, the learning mode (informal vs. formal learning) of L1 and L2 influences the type of procedural memory involved in each language: implicit and automatic in informal acquisition (L1), and explicit and conscious in a formally acquired (typically L2) language [Paradis, 1994]. Differences in recovery for L1 and L2 may therefore reflect, in part, differences in the memory networks involved, rather than damage to a specific structure serving the non-recovered language.

The task in this study required responding according to the similarity in meaning of the two words in a pair. This required memorizing the first word for comparison with the second, followed by comparing the second word's meaning with the memory trace of the first. The task is a variation of Sternberg's single-item memory scanning task [Sternberg, 1966]. In a typical memory-scanning task, comparison in memory is with the memorized item itself (e.g., a specific object or number). In contrast, in this study comparison was with the memorized semantic trace of the item, including synonyms and translations to another language. This task therefore involved operations in language in addition to memory brain networks.

Indeed, effects of experimental conditions on brain responses differed between first word (memorization of meaning) and second word (retrieval and comparison in memory) in the pair. Although no direct comparison between activity to first and second language was performed, a comparison of experimental conditions affecting brain activity to first and second words concurs with this difference in memory processes. For example, current densities among late bilinguals were lower in the mixed than monolinguistic settings in response to first words in the pair, but higher in the mixed than monolinguistic settings to second words in the pair (group × setting interactions in Table I and main setting effect in Table II). These qualitative differences between brain activity to first and second words are not the result of the different time periods used for their analyses. The time periods in the responses to first and second words were selected based on periods of increased activity across brain regions and approximate correspondence to the scalp-recorded components (see earlier section). The timing of such increased activities was later in response to second words compared with first words, in line with the suggested additional processing involved. The differences between brain activities to first and second word would have been much more significant if identical time periods were analyzed (e.g., compare current densities at 540 ms in Figs. 5 and 6). Analyzing time periods defined by spans of increased activity, rather than fixed at times, avoided a confound due to latency differences in the activity to first and second words.

Differences between early and late bilinguals may be indicative of the memory processes among these groups. Earlier studies suggested a phonologic loop in short-term memory, which stores and rehearses speech-based information and is necessary for the acquisition of both native and second-language vocabulary [Baddelay 1992; Buchsbaum and D'Esposito, 2008]. This suggestion implies translation of non-verbal material into verbal terms for its memorization and is compatible with more processing activity in memorizing non-verbal, compared with verbal material, because the former requires additional encoding to verbal terms [Pratt et al., 1997; Wolach and Pratt, 2001]. The results showing higher current densities to first words in the pair among early bilinguals in this study therefore suggest that early bilinguals involve more brain activity in memorizing words in the mixed setting, presumably treating neither language as L1, or translating either language to its counterpart and memorizing a dual representation in both L1 and L2. The latter suggestion is in line with conclusions by Thierry and Wu [2007] and Martin et al. [2009] on dual language representation among early bilinguals. This dual representation results in a readily available memorized first word for comparison with the second word. In contrast, late bilinguals presumably need to "translate" when representations of the memorized first word and the second word are not in the same language (mixed setting). This explanation is also in line with positron emission tomography (PET) results suggesting that phonologic processing plays a predominant role in working memory processing only for the native language of late bilinguals, while the less proficient language is remembered differently [Kim et al., 2002]. The dual language representation in working memory of early bilinguals may also explain the relatively similar late activation among early bilinguals across languages (e.g., Table I, Group × Language interaction).

Conclusions

The results show that distribution of speech processing changes with proficiency and with the linguistic setting in which the words are heard. Left/right hemisphere prominence of speech processing differs between early (<300 ms) and late (>300 ms) processing. In addition, early bilinguals employ a dual representation (in both languages) of memorized words.

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