Second Language Vocabulary Acquisition: Neural Changes and Effects of Transcranial Direct Current Stimulation as Captured by Event-Related Potentials

A thesis by

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Abstract

This thesis explores the neural changes underlying the earliest stages of second language (L2) vocabulary acquisition and the potential facilitatory effects of anodal transcranial direct current stimulation (tDCS) on L2 learning. In a weeklong event-related potential (ERP) paradigm, participants completed less than four hours of L2 vocabulary learning with or without anodal tDCS. Part 1 captures the neural changes due to L2 learning in participants who did not experience anodal tDCS. We focused on the N400 component, a measure of lexicosemantic processing, to measure the degree of L2 learning. Results indicate that beginning L2 learners show rapid neural changes following learning. Part 2 investigated learning mediated L2 N400 changes as a function of anodal tDCS. Despite previous behavioral findings showing facilitation of novel vocabulary acquisition due to anodal tDCS, our results indicate that anodal tDCS may actually inhibit L2 vocabulary acquisition in the form of smaller N400 language learning effects.

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General Introduction

Learning a second language (L2) is a critical step to succeeding in an increasingly linked world. Many studies have shown that becoming bilingual confers not only communicative benefits but also improvements in executive control across both linguistic and nonlinguistic domains (for review, see Bialystok, Craik, Green, & Gollan, 2009). Of particular interest is L2 vocabulary acquisition, an integral part of L2 learning that predicts lexical richness in language production, verbal fluency, reading ability, and reading comprehension (Nation, 1993; Laufer & Nation, 1995; Qian, 2002; Luo, Luk, & Bialystok, 2010). Although most previous L2 vocabulary acquisition studies have utilized behavioral measures to assess learning, a few recent studies using event-related potentials (ERPs) have suggested this methodology might be useful in tracking the effects of L2 acquisition by providing a direct, temporally detailed and sensitive measure of neural changes following learning (e.g., Yum et al., 2014).

Using ERPs, the following studies investigate the effects of learning on L2 processing following minimal instruction (less than four hours). Part 1 examines whether ERP effects of L2 processing found in intermediate bilinguals can also be shown in beginner adult L2 learners: first language (L1) vs L2 word processing differences, translation priming effects, and changes to L2 word processing. Finding these effects in learners with such minimal instruction would not only demonstrate the capacity for neuroplasticity in the adult brain, but also emphasize its rapidity. In Part 2, we investigate whether anodal transcranial direct current stimulation (tDCS) is sufficient to improve L2 vocabulary acquisition. This neurostimulatory technique has been employed in recent behavioral studies to show facilitation of novel vocabulary acquisition (Floel et al., 2008; Fiori et al., 2011; Meinzer et al., 2014). As in Part 1, the degree of L2 learning is captured by ERP changes to L2 word processing before and after learning.

Part I: Neural Changes Underlying Early Stages of L2 Vocabulary Acquisition

Previous research using event-related potentials (ERPs) have shown L2 vocabulary acquisition to be accompanied by neural changes (McLaughlin et al., 2004; Osterhout et al., 2008; Soskey, 2010; Yum et al., 2014). However, while these studies examined beginning L2 adult learners, their assessments followed after weeks or even months of L2 instruction. In the present study, we utilized ERPs to track the neuronal changes during the earliest stages of L2 vocabulary acquisition: naïve learners began to acquire vocabulary in an L2 and were tested within the same week.

When learning words in a new language, learners must first establish knowledge about word form and then about word meaning. Evidence for this learning trajectory comes from McLaughlin et al.'s seminal study examining classroom learners of French (2004). Using a semantic priming lexical decision task in L2, McLaughlin and colleagues demonstrated that learners show a word-pseudoword N400 effect after only 14 hours of instruction, reflecting the ability to differentially process known and unknown word forms. A semantic priming N400 effect, where learners show smaller N400 amplitudes to related than unrelated targets, manifested after 63 hours of instruction, reflecting word meaning activation. This timing difference indicates that word form knowledge precedes word meaning knowledge during learning and suggests that a certain L2 proficiency threshold must be reached prior to any word meaning modulations of the N400. Importantly, the learners showed these N400 effects in the absence of behavioral effects, indicating that ERPs can be a sensitive methodology for tracking early neuronal changes in L2 learners.

Other ERP studies in L2 learners have investigated the processing of L2 words relative to first language (L1) words (Midgley et al., 2009a; Soskey, 2010). These studies reliably demonstrate a N400 language effect where L1 items elicit greater N400 amplitudes than L2 items. More importantly, the magnitude of this language effect changes as a function of L2 proficiency. Soskey demonstrated that learners who were enrolled in Introductory Spanish showed increasingly larger N400s to L2 words as the semester progressed, reducing the magnitude of the N400 language effect as proficiency increases (2010). Specifically, the largest N400 language effect was seen after 34 days of instruction and the smallest after 153 days. Similarly, Midgley and colleagues demonstrated the N400 language effect in both French-English and English-French intermediate bilinguals, indicating that this effect was due to differences between L1 and L2 processing and not due to differences between specific languages (2009a). More importantly, the N400 language effect disappeared in highly proficient bilinguals (Midgley et al., 2009a). This finding, combined with previous work showing increased N400 amplitudes to L2 words as proficiency increases, indicates that the N400 component can be a useful tool for gauging L2 learning progression (Soskey, 2010; Yum et al., 2014). As L2 proficiency increases, so should N400 amplitudes to L2 words while the N400 difference between L1 and L2 words decreases.

Such language effects suggest that beginning L2 learners process their L2 differently than L1. One way that such differences could arise is through differential word meaning access for the two languages. Instantiations of such processing differences in beginning L2 learners have been proposed in models of bilingual lexical processing, including the Revised Hierarchical Model (RHM) (Kroll & Stewart, 1994) and the developmental Bilingual Interactive Activation Model (d-BIA) (Grainger et al., 2010). In both models, early learners access L2 word meaning via lexical mediation of the pre-existing L1 system. In other words, meaning for L2 words is accessed through their L1 word translations, where the L1 words are connected directly to meaning representations. One consequence of this architecture is the strong L2 to L1 connection that allows for fast, lexically mediated backward translation (L2 to L1) relative to slower, meaning mediated forward translation (L1 to L2). ERP support for this comes from N400 translation priming effects in intermediate bilinguals that show earlier effects in the L2 to L1 direction than in the L1 to L2 direction (Alvarez et al., 2003). Asymmetric translation priming effects were also found in intermediate bilinguals for the N250 component, argued to reflect sublexical to lexical form mapping during word processing, with only L1 to L2 direction priming demonstrating such effects (Midgley et al., 2009b). However, a subsequent study increasing prime durations showed L2 to L1 N250 and N400 effects (Schoonbaert et al., 2010).

The present study tested whether the aforementioned ERP effects seen in L2 learners could be captured at the earliest stages of learning – specifically, during the first week of L2 vocabulary acquisition. To do so, we recorded ERPs from learners who receive less than 4 hours of laboratory L2 vocabulary training in a single week. This amount is significantly less than any previous experiment (including McLaughlin et al.'s 14 hour findings) (2004). Across two experiments, we tested for language ERP effects and translation priming ERP effects. Experiment 1 tested for L1/L2 language effects after learning using a go/no-go semantic categorization task that was blocked by language. The N400 component is of main interest in this paradigm, reflecting semantic processing of L1/L2 words (Kutas & Federmeier, 2011). Based on previous research by Midgley et al. (2009a) and Soskey (2010), we anticipated seeing ERP language effects in the learners in the form of larger N400s to L1 items than L2 items. Experiment 2 tested for backward (L2 to L1) unmasked translation priming effects using a translation task. In this paradigm, we were interested in studying both the N250 and the N400 components, previously shown to be modulated by translation priming (Alvarez et al., 2003; Midgley et al., 2009b; Schoonbaert et al., 2010). According to the predictions made by the RHM and the developmental BIA model, we anticipated strong L2 to L1 connections that may manifest as translation priming. However, all previous ERP translation priming studies have utilized intermediate or higher proficiency bilinguals, making the present study one of the first to test such effects at such an early stage of L2 learning. The design of Experiment 2 also allowed for comparisons between pre- to post-learning ERP measures of L2 word processing, an important follow-up to Experiment 1. As in previous work demonstrating growing N400 components as learning progressed, we anticipated larger N400 amplitudes to L2 words following learning as compared to baseline (Soskey, 2010; Yum et al., 2014). Such results would indicate that neural changes rapidly occur after even a few hours of learning.

1. Experiment 1 – Language effects after learning

Naïve Spanish learners engaged in two sessions of vocabulary learning across the span of a week. ERP language effects (comparing L1 and L2 words) were measured after learning during a go/no-go semantic categorization task.

1.1. Method

1.1.1. Participants

Participants were 10 native English speakers (5 females; mean age = 21.3, SD = 3.4) with no or limited exposure to Spanish or any other Romance languages. Prior to learning, participants reported low competency in Spanish in a Likert-scale language background questionnaire (1 to 7 where 1 = below average and 7 = above average): average Spanish speaking ability = 1, average Spanish comprehension = 1, average Spanish reading = 1.1, average Spanish writing = 1, and average Spanish vocabulary = 1.1.

All participants self-labeled as monolingual (not fluent in another language) and were right-handed (Edinburgh Handedness Inventory from Oldfield, 1971) with normal or corrected-to-normal vision and normal neurological profile. All participants gave written informed consent and were compensated for their time, as approved by the Tufts University Institutional Review Board.

The 10 participants were recruited as part of a larger experiment involving transcranial direct current stimulation (tDCS) and language learning. As part of the experiment, each participant in the current study was assigned to the sham stimulation condition in which sub-facilitatory stimulation was delivered to electrodes in an elastic cap (2 mA of direct current via five Ag/AgCl sintered ring electrodes for 30 seconds). Such low levels of stimulation are considered to have no appreciable effect on cortical neural dynamics (Nitsche & Paulus, 2000). Sham stimulation coincided with the first list of each learning session.

1.1.2. Stimuli

One hundred four to eight letter Spanish noncognates, selected from Chapters 3-7 (20 from each chapter) of the Tufts Spanish 1 textbook (*Exploraciones*, Blitt & Casas, 2012), and their English translations were used in the present study. In addition, twelve four to seven letter Spanish body part words and their English translations were also included as probes for the semantic categorization task. Spanish words had a mean word length of 6.29 (range = 4-8) and mean log frequency of 1.58 (range = 0.13-3.1) according to the LEXESP Spanish database (Sebastián-Gallés, Martí, Cuetos & Carreiras, 2000). English translations had a mean word length of 5.16 (range = 3-10) and mean log frequency of 2.02 (range = 0.6 – 3.68) according to the CELEX English database (CELEX, 1993). The English words were significantly shorter in length than the Spanish words ($t(99) = 6.63$, $p < 0.001$).

Pronunciations of all 112 Spanish words were recorded in isolation by a female native Spanish speaker using a Sennheiser PC131 headset (80Hz-15,000 Hz input). Each recording was edited using CoolEdit software to normalize for volume and onset and offset latencies.

Stimuli were blocked by language and presented in a counterbalanced fashion (English first, Spanish second or vice versa) such that each participant saw all 112 Spanish words and 112 English words. All stimuli were randomized within each language-blocked list.

1.1.3. Procedure

1.1.3.1. Learning Paradigm

Participants engaged in two learning sessions, one on Tuesday and one on Thursday, during a single week. The learning paradigm included the 100 Spanish words and 12 Spanish body part probes and their corresponding English translations. Learning consisted of explicit association pairing of each Spanish word with its English translation. Using Qualtrics, each word was shown for 4 seconds with a 2 second pound sign separating each pairing. Audio of the correct pronunciation was played for the presentation of each Spanish word. Participants were asked to repeat each Spanish word out loud following the audio presentation to ensure attention to the task and consistent phonological feedback across participants.

Each participant saw each Spanish-English pair twice per learning session: once in a forward association (L1 → L2) direction and once in a backward association (L2 →L1) direction. Therefore, two lists (each containing the 112 Spanish-English pairs) were made for each learning session, such that the first list presented backward association pairs and the second presented forward association pairs. While the list order remained the same across both learning sessions (backward association learning, followed by forward association learning), the order of the Spanish-English pairs was randomized across each list. In all, each learning session took roughly 1 hour (25 minutes for each list).

1.1.3.2.Post Learning Translation Task

After each learning session, participants performed a two-alternative forced choice task where they chose the correct English translation of one of the 112 Spanish words (backward translation, L2 → L1) or the correct Spanish translation for one of the 112 English words seen in learning phase (forward translation, L1 → L2).The purpose of this task was to gauge the degree of learning from the two learning lists as well as to reinforce learning through feedback.

Half of the 112 Spanish words were presented in a forward translation direction while the remaining half was presented in a backward translation direction, with direction order counterbalanced across participants. After each choice, the correct Spanish-English pairing was presented for three seconds before moving onto the next trial. During this feedback, participants heard and repeated out-loud the audio of the Spanish word pronunciation.

1.1.3.3.Semantic Categorization Task

On the day after the second learning session (Friday), participants returned to the lab to perform a go/no-go semantic categorization task with body parts as probes (see Fig. 1). During the task, participants viewed a fixation cross at the center of the screen for 1 second before the target word appeared on the screen for 800 ms. Participants were told to press a button on a gamepad if the target word was a body part and to refrain from pressing anything if it wasn't. Each word was separated by a 1.5 second blink signal during which participants could move their eyes. The task was blocked by language such that participants saw either all 112 Spanish words or all 112 English translations first. Language order was counterbalanced across participants.

All stimuli were displayed in white Verdana font on a black background on a 19-in. CRT monitor located approximately 150 cm in front of the participant. Participants were asked to remain still and to refrain from blinking until the blink signal.

1.1.4. EEG Recording

For the semantic categorization task, participants sat in a comfortable chair in a dark, sound attenuated room for electrode placement and recording. The electroencephalogram (EEG) was recorded using a 29-channel electrode cap (Electrode-Cap International; see Figure 2 for electrode placements). Loose electrodes were attached below the left eye (LE) to monitor for blinks/vertical eye movements and at the right temple (HE) to monitor for eye horizontal movements. Additional loose electrodes were attached over the left mastoid process (A1) and over the right mastoid process (A2). A1 served as the reference for all electrodes while A2 monitored for differential mastoid activity. All electrode impedances were kept below 5 kΩ, except for the eye electrodes (< 10 kΩ) and the mastoid electrodes (< 2 kΩ). The EEG was continuously sampled at 200 Hz during the experiment while an SA Bioamplifier (SA Instruments, San Diego, CA) amplified the signal at a bandpass of 0.01 and 40 Hz.

1.1.5. Data Analysis

After artifact rejection (5.5% of trials were rejected for ocular artifacts), averaged ERPs were formed for each target word (using -100 and 0 ms baseline) and low-pass filtered at 15 Hz. Time course analysis of mean amplitudes in 100ms intervals spanning 300ms to 600ms post target onset allowed us to capture the effects of the N400 component. Data was analyzed from 9 scalp electrode sites from representative electrodes in the frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) scalp regions (see Figure 2). Analyses of variance (ANOVAs) were conducted using the within-subjects factors of language (English vs Spanish), anterior-posterior electrode position (frontal vs central vs parietal), and laterality (left vs middle vs right). All repeated measures with more than one degree of freedom in the numerator underwent the Geisser and Greenhouse (1959) correction.

1.2. Results

1.2.1. Behavioral Results

On average, participants chose the correct translation in the post-learning session translation task 95.9% of the time (*SD* = 7.9%). On the semantic categorization task, participants showed an average *d*' score of 3.86 (*SD* = 0.35) for the English (L1) block and an average *d'* score of 2.09 (*SD* = 0.98) for the Spanish (L2) block. These scores were significantly different, *t*(9) = 5.86, $p < 0.001$. Importantly the d' score of 2.09 was also significantly better than 0, *t*(9) = 6.76, $p < 0.001$.

1.2.2. ERP Results

Figure 3 shows the ERPs time-locked to target English/L1 words (in black) and target Spanish/L2 words (in red). The difference waves between the two are represented in the form of the voltage maps seen in Figure 4, which reflect the voltages when L2 word ERPs are subtracted from L1 word ERPs.

1.2.2.1. 300-400 ms epoch. In the early standard N400 epoch, there was a main effect of language ($F(1,9) = 5.74$, $p = 0.042$) with L1 words eliciting more negative waves than L2 words (see Fig. 3 and Fig. 4)

1.2.2.2. 500-600 ms epoch. In the late N400 epoch, there was again a main effect of language ($F(1,9) = 6.93$, $p = 0.027$) with L1 words eliciting more positive waves than L2 words (see electrode Pz in Fig. 3 and the voltage map in Fig. 4)

1.3 Discussion

In Experiment 1, native English speakers with no prior Spanish experience learned a set of Spanish words over a period of a week. ERPs were recorded to a go/no-go semantic categorization task after learning where the learners passively read L1 (English) and L2 (Spanish) words. Results indicate that both L1 and L2 words elicit an N400 with clear language effects depending on timing. At all electrode sites, L1 words elicited more negative waves than L2 words in the earliest N400 epoch (300-400 ms). After 400 ms, however, L2 words began to elicit more negative waves than L1 words. This switch was most prominent in the 500-600 ms epoch, where we found a main effect of language. As in Midgley et al., 2009a, this switch in language effect direction appears to be attributed to a delay in the N400s to L2 words by approximately 100 ms.

That we found similar results to Midgley et al., 2009a's intermediate L2 learners is an interesting finding suggesting that neural discrimination between L1 and L2 words can be seen after only a few hours of learning. However, no analogous baseline condition was used for this task to test whether these differences existed prior to learning. This decision was in part due to the inability of participants to engage in semantic categorization for a language they had not learned yet. To address this issue, we conducted a second experiment using a translation task to investigate changes in processing L2 words after a week of learning. This would allow us to estimate the degree of the L1 vs L2 language effect prior to learning as well as test for another effect: translation priming.

2. Experiment 2 – Translation priming effects after learning

In the second experiment, we tested the same participants as in Experiment 1. Prior to and after learning, the participants completed a translation task ('Is this English word the correct translation of the previous Spanish word?') during which ERPs were recorded to Spanish word primes and English word targets. This format allowed for the comparison of 1) translation priming effects before and after L2 learning and 2) changes to L2 word processing before and after learning.

2.1. Method

2.1.1 Participants

The same participants as in Experiment 1 completed Experiment 2.

2.1.2. Stimuli

Experiment 2 also utilized the same stimuli as Experiment 1.

2.1.3. Procedure

The learning paradigm and the post learning translation tasks were the same ones that the participants engaged in during Experiment 1.

2.1.1.1. Yes-No Translation Task

During two ERP sessions (one on Monday – the day before the first learning session – and one on Friday – the day after the second learning session –), participants performed a yes/no translation task. During the task (see Fig. 5), participants held a gamepad and viewed a fixation cross at the center of the screen for 1 second before a Spanish word appeared on the screen for 800 ms. After this, an English word appeared on the screen for 800 ms, followed by a question mark. The question mark remained on the screen until the participants pressed a shoulder button on the gamepad to indicate if they thought the English word was the correct translation for the preceding Spanish word (yes/no). Following a 'yes'/'no' decision about the translation pair accuracy, the next trial appeared.

All 112 Spanish words and body part probes as well as their English translations were presented during each ERP session. 50% of the trials contained correct translation pairs, while the remaining 50% contained incorrect translation pairs. Two lists were created – one for each ERP session – which randomized the pairings between sessions. The gamepad buttons for yes/no were counterbalanced between subjects and between the two sessions.

All stimuli were displayed in white Verdana font on a black background on a 19-in. CRT monitor located approximately 150 cm in front of the participant. Participants were asked to remain still and to refrain from blinking until the question mark sign or during breaks.

2.1.4.EEG Recording

The same EEG recording procedure used in Experiment 1 was used for Experiment 2.

2.1.5. Data Analysis

ERPs were averaged after artifact rejection (4.4% of trials were rejected for ocular artifacts during the first ERP session and 3.3% of trials were rejected during the second ERP session) and formed for two comparisons: change in translation priming effect and change in L2 processing.

2.1.5.1. Translation Priming Effects Before and After Learning

Averaged ERPs were formed for each target English word (using -100 and 0 ms baseline) and low-pass filtered at 15 Hz. Time course analysis of mean amplitudes in 100ms intervals spanning 200ms to 500ms post target onset allowed us to capture the effects of the N250 component (200-300ms) and the N400 component (300-500ms). Data was analyzed from 9 scalp electrode sites from representative electrodes in the frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) scalp regions (see Figure 2). Analyses of variance (ANOVAs) were conducted on the amount of translation priming (unrelated – translation L1 word difference waves) using the within-subjects factors of ERP session (before learning vs after learning), anterior-posterior electrode position (frontal vs central vs parietal), and laterality (left vs middle vs right). All repeated measures with more than one degree of freedom in the numerator underwent the Geisser and Greenhouse (1959) correction.

2.1.5.2. L2 processing Before and After Learning

Using a -100 to 0 ms baseline, averaged ERPs were formed for each Spanish prime word and low-pass filtered at 15 Hz. Time course analysis of mean amplitudes in 100ms intervals spanning 300ms to 600ms post target onset allowed us to capture the effects of the N400 component. Data was analyzed from 12 scalp electrode sites from representative electrodes in the prefrontal (FP3, FPz, FP4), frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) scalp regions (see Figure 2). Analyses of variance (ANOVAs) were conducted using the within-subjects factors of ERP session (before learning vs after learning), anterior-posterior electrode position (prefrontal vs frontal vs central vs parietal), and laterality (left vs middle vs right). All repeated measures with more than one degree of freedom in the numerator underwent the Geisser and Greenhouse (1959) correction.

2.2.Results

2.2.1. Behavioral Results

Prior to learning, participants had an average *d*' score of 0.44 (*SD* = 0.39) on the translation task. After learning, participants had an average *d'* score of 3.17 (*SD* = 1.72) on the translation task. These scores were significantly different, $t(9) = -5.09$, $p < 0.001$.

2.2.2. ERP Results

2.2.2.1. Translation Priming Effect Results

Figure 6 shows the ERPs time-locked to target English/L1 words from the first ERP session (before learning), with the black waves representing unrelated L1 words (previous Spanish/L2 word was unrelated) and the red waves representing translation L1 words (previous L2 word was its translation). Figure 8 shows the same comparison after learning. The degree of translation priming after learning is captured in the voltage maps seen in Figures 7 and 9, which were created by subtracting the translation L1 targets from the unrelated L1 targets. Figure 7 displays the translation priming effect prior to learning and Figure 9 after learning. Finally, Figure 10 demonstrates the change in the translation priming effect due to learning, created by subtracting the translation priming effect from the first ERP session from that of the second ERP session.

2.2.2.1.1. 200-300 ms epoch. In this epoch, there was a main effect of ERP session ($F(1,9) = 8.54$, $p = 0.017$) where the translation priming effect was significantly larger after learning than before learning (see Fig. 7 and 9).

2.2.2.1.2. 300-400 ms epoch. Similarly, there was a main effect of ERP session ($F(1,9) = 19.71$, $p = 0.002$) where the translation priming effect was significantly larger after learning than before learning (see Fig. 7 and 9).

2.2.2.2. L2 Processing Results

Figure 11 shows the ERPs time-locked to Spanish/L2 words from the first (red waves) and second (black waves) ERP sessions. The change in L2 processing from the first to second ERP session is captured in the voltage maps seen in Figure 12.

2.2.2.2.1. 400-500 ms epoch. Analysis revealed a significant interaction between ERP session and Anterior-Posterior electrode positions, $F(3,27) = 4.46$, $p = 0.035$. Subsequent follow-up ANOVAs separated by electrode position (prefrontal vs frontal vs central vs parietal) indicated an almost significant main effect of ERP session in prefrontal electrodes (FP1, FPz, FP2) only ($F(1,9) = 3.43$, $p = 0.097$) where ERPs to L2 words were larger in the second session than the first (see Figure 12).

2.2.2.2.2. 500-600 ms epoch. In this epoch, there was a significant interaction between ERP session and Anterior-Posterior electrode positions, $F(3,27) = 13.77$, $p < 0.001$. Subsequent follow-up ANOVAs separated by electrode position (prefrontal vs frontal vs central vs parietal) revealed a significant main effect of ERP session in prefrontal electrodes ($F(1,9) = 5.72$, $p = 0.04$) and an almost significant main effect of ERP session in frontal electrodes (F3, Fz, F4),

$F(1,9) = 3.67$, $p = 0.088$, where ERPs to L2 words were larger in the second session than the first (see Figure 12).

2.3 Discussion

Experiment 2 tested the same participants in both baseline and post-learning ERP translation tasks. Participants demonstrated better performance on the translation task after learning, as seen in the significant improvement in *d'* scores from the first to the second ERP session. Task design (unmasked L2 prime followed by L1 target) allowed for the comparison between unrelated and translation targets in order to gauge the degree of translation priming across ERP sessions. Results revealed significant effects of learning on the translation priming effects during the N250 and N400 epochs: such effects were greater after learning than at baseline (see Fig. 9). Comparisons of ERPs to L2 words before and after learning revealed significant effects of learning during the late N400 epoch (400-600 ms) in anterior electrodes. At these electrode positions, L2 words elicited greater amplitude N400s following learning than at baseline, supporting previous work on L2 N400 amplitude changes due to learning (Soskey, 2010; Yum et al., 2014).

3. General Discussion

In two experiments, we tested L2 processing of adult L2 learners who had less than 4 hours of L2 vocabulary instruction. Experiment 1 tested for ERP language effects using a go/no-go semantic categorization task while Experiment 2 tested for ERP translation priming effects and L2 processing changes using a yes-no translation task. In both experiments, L2 learners elicited effects similar to those seen in previous studies utilizing intermediate bilinguals. Behavioral data from the post learning translation task indicate that participants were highly accurate in translating from L2 to L1 and from L1 to L2 when presented in a two-forced-choice format. Significant effects of learning on the Yes-No translation task behavioral performance also support the rapid learning of L2 words in these participants. Such performance is in line with previous research showing similar behavioral learning in lab settings (Yum et al., 2014).

3.1. L1 vs L2 Language Effect

As in previous experiments, the results from Experiment 1 indicate that learners in early stages of L2 acquisition demonstrate an N400 language effect where L1 words elicit more negative N400s than L2 words, particularly at parietal electrode sites. Results also reveal a delay in the N400 component for L2 words similar to that seen in Midgley and colleague's experiment with intermediate bilinguals (2009a). This latency difference is partially responsible for the significant language effect from 500-600 ms in which L1 words elicited more positive waves than L2 words. Importantly, this delay is in line with hypotheses of meaning access according to both the RHM and the d-BIA models of bilingual word processing (Kroll & Stewart, 1994; Grainger et al., 2010). In the earliest stages of L2 acquisition, meaning access for L2 words is proposed to be lexically mediated (requires activation of its L1 translation) whereas no such interference exists for L1 words. In other words, meaning can be activated directly for the L1 words in Experiment 1. For the L2 words, meaning is activated indirectly via L1 word activation. This indirect route may be responsible for the delay in the N400, thought to reflect semantic access and processing, seen for the L2 words (for review of the N400, see Kutas & Federmeier, 2011).

Critically, the participants in the present study received less than 4 hours of L2 instruction prior to the task, compared to the beginner and intermediate bilinguals in previous studies (Midgley et al., 2009a; Soskey, 2010). Soskey's learners were at least 34 days into the semester of language learning before they were tested and revealed to show the N400 language effect (2010). That the same effect is found after 2 days of learning in the present study indicates that the language effect may be pervasive even after minimal instruction. One interpretation of the effect is the difference in orthographic neighborhood size processing between languages (Midgley et al., 2009). This explanation is based on monolingual findings indicating that words with many orthographic neighbors (words that differ from each other by one letter) elicit larger amplitude N400s than those with fewer orthographic neighbors (Holcomb et al., 2002). Beginning L2 learners have a much larger L1 lexicon than an L2 lexicon, with the former containing many more neighbors than the latter. This manifests as smaller N400s for L2 words relative to L1 words and explains why this language effect diminishes as L2 proficiency increases: as learners progress in L2 learning, the L2 lexicon increases and thus more L2 neighbors are activated during processing. Given this explanation, it is no surprise that after two days of learning, a robust language effect can be seen in the N400 epoch.

3.2.L2 Processing Changes Due to Learning

As a follow-up to Experiment 1, Experiment 2 allowed for the comparison of L2 word processing before and after learning. We showed that L2 words elicited larger N400s after learning than at baseline, a finding that has been shown in beginning L2 learners in previous studies (Soskey, 2010; Yum et al., 2014). While our N400 effect was not seen in typical centro-parietal scalp regions, such anterior distributions of the effect also been shown in a recent L2 learning study by Yum and colleagues (2014). Importantly, our experiment showed this effect in the first week of learning after less than 4 hours of L2 instruction. Such findings indicate that neural changes are perhaps more rapid than previously shown and add to the previous L2 acquisition work supporting adult neuroplasticity.

These results combined with the language effects from Experiment 1 suggest that the language effect may have been larger in the first ERP session had it been tested. Recall that Experiment 1 showed smaller N400s to L2 words than L1 words in the second ERP session, after learning had occurred. Meanwhile, Experiment 2 showed smaller N400s to L2 words in the first ERP session than the second ERP session. Given these two results, we would anticipate a larger N400 difference between L2 words and L1 words in the first ERP session, before learning had occurred. If this was the case, then the decreased language effect from the first to the second ERP session would follow the trajectory found in previous work. As learning progresses, the L1 vs L2 N400 language effect decreases (Midgley et al., 2009a; Soskey, 2010).

3.3. Backward Translation Priming Effect

Results from Experiment 2 indicate a clear effect of learning on the backward translation priming effect: unrelated L1 targets elicited higher amplitude N400s than translation L1 targets only after learning and not prior to learning (see change due to learning in Fig. 10). This effect was robust from 200-400 ms, an early time-window for the N400 component. Previous studies using masked translation priming have shown clear N250 and N400 effects of translation priming in intermediate and proficient bilinguals. Although a significant translation priming effect was found in the traditional N250 epoch (200-300 ms), no clear N250 component was seen in the waves (see Fig. 8).

The presence of a backward translation priming effect in these early L2 learners again supports the predictions of the RHM and the d-BIA. Recall that these models propose a strong

L2 to L1 connection that allows for strong L1 translation activation whenever an L2 word is activated. By this logic, seeing the unmasked L2 prime would facilitate the activation of the L1 target only if the target is the translation of the prime. In such cases, L1 target processing would lead to attenuated N400s that reflect the ease of semantic processing, relative to cases where the L2 prime was not the translation of the target. Alternatively, it is possible that the 800 ms stimulus-onset-asynchrony (SOA) as well as the unmasked primes allowed for participants to make overt translations prior to the target appearance, leading to a translation priming effect that is more akin to L1-L1 priming. Such an explanation has been proposed for Alvarez et al.'s 2003 results by Midgley and colleagues (2009b). However, even if this overt translation strategy was used, the presence of a priming effect indicates that the learners are correctly translating the L2 items and have activated the necessary semantic representations by the time the target has appeared.

4. Conclusion

The present study explored the neural changes underlying the earliest stages of L2 vocabulary acquisition. Similar to those shown in intermediate bilinguals, our learners showed N400 language effects demonstrating differences in processing L1 vs L2. Additionally, L2 words elicited larger N400 components following learning as has been shown in previous longitudinal L2 learning studies. To our knowledge, this is the first study to show the presence of the translation priming effect in L2 learners with such minimal instruction (less than 4 hours in a week). Previous ERP studies looking at masked or unmasked translation priming have only utilized intermediate or proficient bilinguals (Alvarez et al., 2003; Midgley et al. 2009; Schoonbaert et al., 2010). These results speak to the rapid plasticity that occurs as learners begin to learn a new language and show that even minimal instruction can lead to neuronal changes that can be captured using ERPs.

Part II: ERP measures of anodal Transcranial Direct Current Stimulation (tDCS) effectson Second Language Vocabulary Acquisition

1. Introduction

Vocabulary acquisition is a critical component of second language (L2) acquisition, predicting performance in both L2 production and comprehension (Nation, 1993; Laufer & Nation, 1995; Qian, 2002). Given its importance, we sought to improve L2 vocabulary acquisition using a neurostimulatory intervention: anodal transcranial direct current stimulation (tDCS). The use of event related potentials (ERP) in the present study allowed for quantitative measures of the efficacy of tDCS on L2 vocabulary acquisition.

1.1.Transcranial Direct Current Stimulation

tDCS is a noninvasive, neurostimulatory technique where a low, constant current (0.5-2 mA) passes between electrodes placed on the scalp. Although electrical stimulation has been used to alter brain processing for centuries, tDCS use for both clinical and cognitive applications has soared in the last few decades after studies reliably demonstrated the facilitatory and inhibitory effects of direct current stimulation on cortical excitability (Priori, 2003; Nitsche & Paulus, 2000; Nitsche & Paulus, 2001).

The mechanism and neurophysiological effects of tDCS differ depending on the direction of current flow toward a neural target. Anodal stimulation – where current flows inward – of a target brain region increases cortical excitability by depolarizing neuronal resting membrane potential and is thought to elicit facilitatory effects on processing. On the other hand, cathodal stimulation – where current flows outward – decreases cortical excitability by hyperpolarizing neuronal resting membrane potential, which is thought to lead to inhibitory effects on processing (for review, see Nitsche et al., 2008). Additionally, tDCS effects continue after stimulation has ended: studies have shown sustained intracortical excitability for up to 90 minutes following only 13 minutes of anodal tDCS (Nitsche & Paulus, 2001; Nitsche et al., 2005; Nitsche et al., 2007). Neurophysiological testing with neurotransmitter receptor agonists and antagonists reveal that while only neuronal membrane resting potential is altered during anodal and cathodal stimulation, the sustained aftereffects are due to synaptic strength modification (for review, see Stagg & Nitsche, 2011). In particular, the increase in intracortical synaptic strength following anodal stimulation is similar to the synaptic plasticity induced by long-term potentiation, the mechanism thought to underlie learning and memory (Stagg & Nitsche, 2011).

Since anodal tDCS acts via mechanisms that are likely to be similar to those implicated in learning and memory, it is an attractive technique for testing learning and memory paradigms. In fact, studies have found improvements in probabilistic classification learning and working memory (3-back letter task) performance in both healthy subjects and Parkinson's patients following prefrontal cortex anodal stimulation (Kincses et al., 2004; Fregni et al., 2005; Boggio et al., 2006). Other studies show visuo-motor learning and motor perception improvements after anodal stimulation to the left V5 (Antal et al., 2004a; Antal et al., 2004b). Given such promising results in a variety of cognitive domains, it is surprising that, at this time, only a handful of language learning studies on healthy subjects using tDCS have been reported (Floel et al, 2008; deVries et al., 2010; Fiori et al., 2011; Meinzer et al., 2014).

1.2.Anodal tDCS & Language Learning

Of the few studies examining the effects of tDCS on language learning in healthy subjects, three tested the effects of anodal tDCS on artificial vocabulary acquisition (Floel et al., 2008; Fiori et al., 2011; Meinzer et al., 2014) Floel et al. were the first to find that anodal, but not cathodal, tDCS stimulation for 20 minutes during artificial vocabulary learning could improve subsequent performance on a translation task (2008). Their within-subject study gave participants anodal, cathodal, and sham tDCS over the left superior temporal cortex – Wernicke's area – (electrode CP5 in the 10-20 EEG system) across three separate learning sessions (2008). In each learning session, 1mA of tDCS (anodal or cathodal) was presented over 20 minutes (or <30 seconds for the sham condition) while participants completed 30 minutes of implicit association learning of 30 pseudowords (*e.g.* picture of a tree paired with the sound 'enas'). A translation task containing correct or incorrect pairings of the new words with their L1 translation immediately followed learning. Results showed that while accuracy scores on the translation task were not significantly different between the cathodal and sham conditions, participants were significantly more accurate following anodal stimulation. However, this effect was short-lived, as there were no significant differences across the three conditions during a follow-up translation task a week later (2008).

Subsequent work on artificial word learning provided additional support for anodal tDCS's facilitation of vocabulary acquisition. Like Floel et al. (2008), Fiori et al. used a within-subject design to test the effects of anodal or sham tDCS of Wernicke's area (electrode CP5) during artificial vocabulary acquisition (2011). However, stimulation in Fiori et al.'s study did not occur during learning, but during testing. After only five minutes of explicit picture association learning of 20 pseudowords (picture of an object paired with a word) and five minutes of feedback learning (correct or incorrect picture pairs), subjects completed a picture naming task using the newly learned words while undergoing 1 mA anodal or sham stimulation for twenty minutes. Although no difference in accuracy was found between the tDCS conditions, subjects gave faster correct answers during the anodal stimulation condition compared to the sham. This result, combined with that of the previous tDCS artificial vocabulary acquisition study, suggests that anodal tDCS to Wernicke's area at stimulation site electrode CP5 can lead to improved behavioral performance on translation tasks (Fiori et al., 2011; Floel et al., 2008). However, it is uncertain whether these results were also as short-lived as those in Floel et al. (2008).

To rectify this, Meinzer et al. sought to improve upon both previous studies of anodal tDCS effects on artificial vocabulary acquisition by attempting to prolong the behavioral performance advantages using multiple tDCS sessions (2014). Participants were given either 1 mA of anodal or sham tDCS during explicit picture association learning of 120 pseudowords. These training sessions occurred daily for five consecutive days. Results indicate that anodal tDCS not only led to faster learning (better accuracy on recall and recognition tasks) than sham tDCS across the five days, but also resulted in a significantly higher accuracy for the recall task a week later (2014). These accuracy results corroborate those found in Floel et al., and also suggest that multiple tDCS sessions may lead to longer lasting behavioral advantages of vocabulary acquisition (2008).

1.3.Present study

Given the previous research indicating behavioral improvements in artificial vocabulary acquisition through the use of anodal tDCS, the present study tested whether such improvements could be seen during L2 vocabulary acquisition. Though artificial vocabulary learning paradigms allow for easier recruitment and better control of stimuli properties, a considerable disadvantage is the lack of communicative benefits of learning nonwords. Since a fundamental role of language is to allow for communication between speakers, teaching L2 vocabulary provides a significant motivational advantage over teaching artificial vocabulary (Dornyei, 1998). Additionally, the use of L2 vocabulary stimuli provides a more representative account of how anodal tDCS can influence vocabulary acquisition in an ecologically valid setting.

The region of interest for stimulation was the left posterior superior temporal gyrus (BA22 or LPSTG). This region, the location of Wernicke's area, was targeted by all three previous studies showing significant facilitatory anodal tDCS effects on artificial vocabulary acquisition (Floel et al., 2008; Fiori et al., 2011; Meinzer et al., 2014). In bilinguals, the LPSTG is activated during language switching in both L1 and L2 and is more activated for late than early bilinguals (Luk et al., 2012; Tomasino et al., 2014; Waldron & Hernandez, 2013). The latter contrast is tied to the activation of the left STG during lexical retrieval of less frequent words (Graves et al., 2007). In late bilinguals, such as the participants of this present study, lexical retrieval of L2 words would involve a similar mechanism as that of less frequent words for monolinguals, involving activation of the left STG (Waldron & Hernandez, 2013). Additionally, this region is implicated in the retrieval and processing of lexical phonology, given its activation during silent reading of words, pseudohomophones, and pseudowords (Graves et al., 2008; Simos et al., 2002; Liebenthal et al., 2005).

The present study used ERPs, in addition to behavioral measures, to gauge the degree of learning due to stimulation. The inclusion of electrophysiological recordings provides a more temporally sensitive measure of any observed effects of anodal tDCS on language learning. In addition, neural changes during word processing could be tracked as baseline and post-learning ERP recordings will allow for a comparison of the L2 words before meaning is learned, and after. Of particular focus is the N400, as this component is sensitive to lexico-semantic processing (Kutas & Federmeier, 2011).

Previous ERP studies of L2 vocabulary acquisition have shown modulations to the N400 as well as a later positive component (P600 or late positive component, LPC) due to learning. McLaughlin et al.'s seminal work on early neural changes following L2 acquisition showed differences in the N400 as a function of lexicality: L2 words elicited smaller N400 amplitudes than L2 pseudowords (2004). Importantly, this discrimination was found in learners after only 14 hours of L2 instruction and was not shown in the behavioral results. The latter finding demonstrated the sensitivity of ERPs to learning effects that are not shown in behavior, supporting the use of electrophysiological measures in L2 acquisition studies. In another study, students who were enrolled in an introductory Spanish class displayed increasingly larger (more negative) N400s to L2 words as proficiency increased over the course of the semester (Soskey, 2010). This growth of the L2 word N400s was shown to approach the N400s of L1 words, interpreted as L2 processing becoming more L1-like as proficiency increases. A recent study on Chinese vocabulary acquisition in a lab setting demonstrated similar N400 growth to Chinese words as learning progressed (Yum et al., 2014). This N400 learning effect had an anterior distribution and was shown for fast learners (based on behavioral performance). Slow learners, on the other hand, demonstrated a later effect in posterior electrodes where L2 words elicited more positive going waves as learning progressed. This later posterior positivity (which lasted from approximately 400-600ms in Yum and colleague's 2014 study) was shown to arise earlier after L2 learning than at baseline (Stein et al., 2006). Such latency differences were found after 5 months of German acquisition by native English speakers. In the same study, Stein and colleagues discovered the N400 to be of a shorter duration following learning (2006). Taken together, the existing research suggests that the N400 as well as the later positivity is sensitive to L2 proficiency and could be used to gauge the degree of L2 learning in participants.

While previous behavioral tDCS experiences indicate facilitation of novel vocabulary acquisition in anodal over sham stimulation conditions, the effects of anodal vs sham tDCS in the context of ERP measures to L2 learning have never been studied before. Despite this, we anticipated both stimulation groups to show larger N400s to L2 words after learning than at baseline given previous ERP studies on L2 learning. Should one stimulation group (anodal or sham) lead to better L2 learning than the other, then we should expect larger N400 (and possibly later positivity) growth for the facilitated group compared to the other.

2. Method

2.1. Study Overview

In this double-blind, sham-controlled tDCS study, participants completed two L2 vocabulary learning sessions concurrent with either anodal or sham tDCS over the span of a week. ERP measures were taken prior to and after learning to track changes in L2 processing.

2.2. Participants

Twenty healthy native English speakers between the ages of 18 and 30 (7 females; mean age = 21.3, SD = 3.1) participated in the study. 10 participants were randomly assigned (double blind) to the anodal stimulation condition and the other half to the sham condition. Participants had no or limited exposure to Spanish or any other Romance languages. During screening, participants reported low competency in Spanish on a language background questionnaire (Likert Scale 1 – 7; 1 = below average, 7 = above average): average Spanish speaking ability = 1.1, average Spanish comprehension = 1.25, average Spanish reading = 1.25 average Spanish writing = 1, and average Spanish vocabulary = 1.15.

All participants fulfilled the inclusion criteria: 1) Monolingual (not fluent in another language), 2) right-handed (Edinburgh Handedness Inventory from Oldfield, 1971), 3) Normal or corrected-to-normal vision, 4) No psychotropic medication, 5) No history of learning disabilities, 5) No history of head injuries, brain-related conditions, or neurological or psychiatric disorders, and 6) No history of seizures. All participants gave informed consent and were compensated for their time. The study was approved by the Tufts University Institutional Review Board

2.3. Stimuli

Stimuli included 100 four to eight letter Spanish noncognates selected from the Tufts Spanish 1 textbook (*Exploraciones*, Blitt & Casas, 2012) and their corresponding 100 English translations. Using the LEXESP Spanish database, the Spanish words had a mean length of 6.29 (range = 4-8) and mean log frequency of 1.58 (range = 0.13-3.1). Using the CELEX English database, the English translations had a mean length of 5.16 (range = 3-10) and mean log frequency of 2.02 (range = 0.6-3.68). The English words were significantly shorter in length than the Spanish words ($t(99) = 6.63$, $p < 0.001$).

A female native Spanish speaker recorded the pronunciation of each Spanish word (in insolation with a Sennheiser PC131 headset, 80Hz-15,000Hz input). CoolEdit software was used to edit each recording to normalize for volume and onset/offset latencies.

2.4. Transcranial Direct Current Stimulation (tDCS)

2.4.1. Computational Model of tDCS induced Electric Fields

Using computational modeling software HDExplore (v.2.3), the EEG cap positions of the center and 4 surround electrodes were calculated to best direct the electric field to the region of interest: the left posterior superior temporal gyrus. Given an MNI position of {-52, -31, 3}, the corresponding center anodal electrode was placed on position TP7 with the four surround electrodes placed on positions PO7, FT9, C5, and FT7 of the Modified Combinatorial Nomenclature (MCN) EEG system.

2.4.2. tDCS procedure

Anodal and sham tDCS was delivered using a battery-based constant current generator connected to a 4x1 multichannel stimulator adapter. Five Ag/AgCl sintered ring electrodes were attached to plastic holders filled with conductive gel and positioned on the EEG cap in the 4x1 configuration derived from the computational model, with the central electrode positioned over TP7. A code was used to deliver the tDCS in order to blind the researcher to the type of stimulation (sham versus anodal). For both stimulation types, a ramp up time of 10 seconds was used to set the current to its designated mA (2 mA for both sham and anodal conditions). In the sham condition, the current was ramped down after 30 seconds, leaving no lasting effects on neural function while simulating the sensation of stimulation. In the anodal condition, the current was ramped down to zero over 10 seconds after 20 minutes of stimulation duration. During tDCS, participants regularly reported their sensation rating on a 1-9 Likert scale approximately every five minutes, with 1 indicating no pain or discomfort and 9 indicating a considerable amount of pain or discomfort.

2.5 Procedure

2.5.1. Learning Paradigm

In a single week, participants completed two learning sessions (Tuesday; Thursday). During each learning session, participants studied the 100 Spanish words via association learning: each Spanish word was paired with its English translation. The words were displayed using Qualtrics survey software, which showed each word for 4 seconds with a 2 second pound sign separating each pair (Qualtrics, Provo, UT). Spanish pronunciation was played during the presentation of each Spanish word and participants were asked to repeat it out loud. Such repetition ensured attention to the task and consistent phonological feedback across participants.

Participants studied each Spanish-English pair twice per learning session: 1) in a forward association (L1 → L2) direction and 2) in a backward association (L2 → L1) direction. As such, two lists (each containing all Spanish-English pairs) were created for each learning session, with the first list presenting pairs in the backward direction and the second list presenting pairs in the forward direction. Across both learning sessions, participants saw the backward association list first, followed by the forward association list. The order of the Spanish-English/English-Spanish pairs was randomized across the four total lists.

Anodal or sham stimulation began with the first list in each learning session. Each list lasted for approximately 25 minutes with a 5 minute break in between (for a total of approximately one hour of learning per session). During the break, the tDCS cap was removed from the participant. The second list was then completed without stimulation, as intracortical excitability elicited by anodal tDCS persists for up to 90 minutes after stimulation ends (Nitsche & Paulus, 2001; Nitsche et al., 2005; Nitsche et al., 2007).

2.5.2. Post Learning Translation Task

After each learning session (Tuesday; Thursday), participants completed a two-alternative translation task. The task required participants to choose the correct English translation of a Spanish word (backward translation, L2 → L1) or the correct Spanish translation of an English word (forward translation, L1 → L2). The translation task contained all of the Spanish words encountered during the learning session, with half of words presented in the backward translation direction and the remaining half in the forward translation direction. Translation direction order was counterbalanced across the two learning sessions.

For each trial, participants received feedback in the form of the correct Spanish-English translation pairing. This pairing was presented for three seconds after each translation choice and included audio of the Spanish pronunciation. Participants were asked to repeat the Spanish word aloud during the feedback. This post learning translation task gauged the amount of Spanish learning for each participant and also provided another learning opportunity through feedback.

2.5.3. Explicit Backward Direction Translation Task

In two ERP sessions, one day before the first learning session (Monday) and one day after the second learning session (Friday), participants performed an explicit backward direction translation task. During the task (see Figure 13), participants viewed a Spanish word for 800 ms, followed by 'xx'. The 'xx' remained on the screen until the participant provided the English translation of the Spanish word aloud. Participants were also allowed to pass if they were unsure of the translation. Upon hearing their response, the experimenter pressed one of two buttons (one signifying a correct response while the other, an incorrect response) and a blink sign appeared for 2 seconds. After the blink sign, the next trial began. All 100 learned Spanish words were presented in this fashion, with their order randomized for both sessions. A practice task, containing Spanish number words to be translated, was given to each participant at the beginning of the session to familiarize them with the task.

2.5.4. EEG Recording

Participants completed the explicit backward direction translation task in a dark, sound-attenuated room with concurrent electroencephalogram (EEG) recording. EEG was recorded using a 29-channel electrode cap (Electrode-Cap International, see Figure 2 for electrode placements). An additional four loose electrodes were attached below the left eye (LE) to monitor for blinks/vertical eye movements, at the right temple (HE) to monitor for eye saccades, and over the two mastoids (A1 and A2). The left mastoid electrode (A1) served as the reference for all electrodes while the right mastoid electrode (A2) monitored for differential mastoid activity. Electrode impedances were kept under 5 kΩ with the exceptions of the eye electrodes (< 10 kΩ) and the mastoid electrodes (< 2Ω). EEG was continuously sampled at 200Hz and amplified at a bandpass of 0.01 and 40Hz (SA Bioamplifier, SA Instruments).

2.5.5. Data Analysis

ERP data were formed after artifact rejection (7.4% of trials were rejected for ocular artifacts during the first ERP session and 5.4% of trials during the second ERP session). We averaged ERPs timelocked to the onset of each Spanish word, using a -100 and 0 ms baseline, followed by a low-pass filter (15Hz). Time course analysis of mean amplitudes in 100ms intervals spanning 200ms to 600ms post target onset allowed us to capture the effects in the N400 and P600/LPC epochs. Data was analyzed from 9 scalp electrode sites from representative electrodes in the frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) scalp regions (see Figure 2). Analyses of variance (ANOVAs) were conducted using the between-subjects factor of tDCS (sham vs anodal) and the within-subjects factors of Session (before learning vs after learning), anterior-posterior electrode position (frontal vs central vs parietal), and laterality (left vs middle vs right). The Geisser and Greenhouse correction was applied to all repeated measures with more than one degree of freedom (1959).

3.Results

3.1. Behavioral Results

On average, participants in the sham condition completed the post learning session translation task with 95.9% accuracy (*SD* = 7.9%) while those in the anodal condition performed at 93.8% accuracy (*SD* = 9%). This difference was not significant ($t(18) = 0.584$, $p = 0.567$).

On the explicit backward direction translation task, there was a main effect of learning between the first and second ERP session on accuracy: $F(1,18) = 233.2$, $p < 0.001$. Across all participants, accuracy on the task in the first ERP session (before learning) was on average 10% (*SD* = 7%) while accuracy in the second ERP session (after learning) was 71.5% (*SD* = 21.7%). However, the interaction between ERP session and tDCS group was not significant, $F(1,18) = 0.104$, $p = 0.751$. After learning, the sham group demonstrated an average of 62.8% increase in accuracy while the anodal group demonstrated an average of 60.2% increase in accuracy.

3.2. ERP Results

For the sham group, the ERPs time-locked to Spanish/L2 words from both ERP sessions can be seen in Figure 14. The black waves represent L2 word processing after learning and the red waves represent L2 word processing before learning. Figure 15 captures the effect of learning on L2 processing in the sham group in the form of voltage maps, created by subtracting the L2 words before learning from those after learning.

For the anodal group, the ERPs time-locked to L2 words from both ERP sessions can be seen in Figure 16, with the black waves representing L2 word processing after learning and the red waves representing L2 processing before learning. The difference in L2 processing due to learning is seen in the voltage maps in Figure 17: ERPs to L2 words before learning were subtracted from those to L2 words after learning.

3.2.1. 200-300 ms epoch. Analyses revealed a significant three way interaction (Stimulation x Session x AnteriorPosterior electrode position), F (2,18) = 7.97, p = 0.007. Follow-up analyses of the Stimulation x Session interaction at each electrode row revealed a significant effect in frontal electrodes F3, Fz, F4 (F(1,9) = 5.17, p = 0.049) and no significant effect at the central or parietal electrodes. Looking at each stimulation group separately to decipher this interaction, there was an almost significant effect of learning in the sham (F(1,9) = 3.63, p = 0.089) but not the anodal group in the frontal electrodes (see Figure 15 vs Figure 17). Neither sham nor anodal groups showed significant effects of learning in the central or posterior electrodes.

3.2.2. 300-400 ms epoch. Analyses again revealed a significant three way interaction (Stimulation x Session x AnteriorPosterior electrode position), F (2,18) = 6.44, p = 0.018. Follow-up analyses of the Stimulation x Session interaction at each electrode row revealed an almost significant effect in frontal electrodes F3, Fz, F4 (F(1,9) = 2.33, p = 0.1615) contrasted with the nonsignificant effects in central and parietal electrodes. Looking at each stimulation group separately, there was a significant effect of learning (larger N400s to L2 words after learning) in the sham but not the anodal group in frontal electrodes ($F(1.9) = 12.89$, $p = 0.0058$) and central electrodes ($F(1,9) = 5.23$, $p = 0.048$) but not parietal electrodes (see Figure 15 vs Figure 17).

3.2.3.400-500 ms epoch. In this epoch, there was no significant effect or interaction with stimulation group. However, results showed a significant interaction between Session x AnteriorPosterior electrode position ($F(2,18) = 17.27$, $p< 0.001$). Follow-up analyses of the Session main effect at each electrode row revealed an almost significant effect at frontal electrodes F3, Fz, F4 only ($F(1,9) = 5.05$, $p = 0.051$) where L2 words were more negative after learning than before learning. Given that there was no interaction of this effect with stimulation group, anodal and sham groups did not significantly differ in this anterior negativity.

3.2.4. 500-600 ms epoch. As in the previous epoch, results showed a significant interaction between Session x AnteriorPosteriorelectrode position ($F(2,18) = 44.28$, $p< 0.001$). Follow-up analyses of the Session main effect at each electrode row revealed a significant effect at frontal electrodes F3, Fz, F4 ($F(1,9) = 6.67$, $p= 0.0295$) where L2 words elicited more negative going waves after learning than before learning. In contrast, parietal electrodes P3, Pz, P4 showed a significant effect ($F(1,9) = 23.25$, $p< 0.001$) such that L2 words elicited more positive going waves in the second session (after learning) than in the first session (before learning). The lack of interaction between this effect and stimulation group indicates that anodal and sham groups did not significantly differ in these anterior negativity and posterior positivity effects.

4. Discussion

The present study used ERP measures to test whether anodal tDCS could improve L2 vocabulary acquisition. We predicted that both sham and anodal stimulation groups should show larger N400s to L2 words following learning, based on previous ERP studies on beginning L2 vocabulary acquisition (Soskey, 2010; Yum et al., 2014). Additionally, we anticipated potential modulations to a later posterior positivity as has been seen in previous cases (amplitude: Yum et al., 2014; latency: Stein et al., 2006).

Behavioral measures from both the post learning translation task (given after each tDCS accompanied learning session) and the explicit backward direction translation task (given at each ERP session) demonstrated that participants successfully learned the 100 Spanish words over the course of the week. Both anodal and sham stimulation groups showed high accuracy in the post learning translation tasks, with no differential effect of stimulation shown. Similarly, both groups showed an approximately 60% increase in accuracy from baseline to after learning in the backward direction translation task. Again, no effect of stimulation was found, indicating that sham and anodal participants were behaviorally indistinguishable after L2 learning. These behavioral results run contrary to those shown in previous studies on tDCS and vocabulary learning, which have demonstrated better behavioral performance in anodal stimulation groups than sham groups (Floel et al., 2008; Fiori et al., 2011; Meinzer et al., 2014). We'll return to the implications of this finding below.

ERP results, on the other hand, indicate a difference between sham and anodal groups. Comparisons between baseline and post learning ERPs reveal that for both groups, learning elicited larger anterior negativities and posterior positivities, as shown in the significant Session x AnteriorPosterior electrode position interactions from 300-600 ms (see Figures 15 and 17). Interestingly, it was the sham stimulation group that showed larger N400 changes to learning than the anodal group, particularly in anterior electrodes and in the early phase of the N400 (300-400 ms). A later posterior positivity effect to learning was also shown in both groups, with no significant group by learning session interactions (see 500-600 ms in Figures 15 and 17). In other words, sham and anodal groups did not differ in their posterior positivity effects but did in their anterior negativity (N400) effects.

These results demonstrate that ERP effects of L2 acquisition appear to manifest in anterior negativity/posterior positivity changes that are significant after only two learning sessions in the span of a week. This anterior negativity and posterior positivity are similar to those found in Yum et al.'s previous work on L2 vocabulary acquisition (2014). However, we demonstrated such results after only two sessions in one week while the previous study spanned months. Like McLaughlin et al.'s work (2004), the present study highlights the sensitivity of ERPs to learning effects while in the absence of behavioral findings: only the ERPs (and not behavioral results) revealed differences between sham and anodal groups. Contrary to what was found in previous behavioral studies on anodal vs sham tDCS on language learning, anodal tDCS appears to slow the development of L2 electrophysiological changes, given that the sham group showed greater effects of learning in the ERPs.

The lack of behavioral difference between the two stimulation groups as well as the fact that the sham group showed larger electrophysiological effects of learning than the anodal group, suggests that anodal tDCS does not confer any benefits to L2 vocabulary acquisition and may even hinder L2 processing. But how can we reconcile such results with those from previous behavioral studies showing facilitatory effects of anodal tDCS on language learning ((Floel et al., 2008; Fiori et al., 2011; Meinzer et al., 2014)? One possibility lies in the difference between the stimuli used in the present study and the previous studies. In the present study, we utilized real L2 words (Spanish) as compared to the invented pseudowords used in all three studies showing facilitatory anodal tDCS effects. In two of the previous studies, the invented pseudowords adhered to the phonology and orthography of participants' first language (L1) (Floel et al., 2008; Meinzer et al., 2014). In the third, the pseudowords followed orthographic and phonological patterns different than those of the participants' L1 (Fiori et al., 2011). Learning words in a L2 is vastly different than learning pseudowords that look and sound like words in a first language. The former requires the formation of new orthographic and phonological rules while the latter utilizes already familiar orthographic and phonological systems. As such, L2 vocabulary acquisition might be more difficult than L1 pseudoword acquisition. Accordingly, it is possible that the effects of anodal tDCS are sufficient for acquiring new L1 items (i.e., pseudowords) but are not sufficient foracquiring new words in a second language. Consistent with this explanation, the one study that utilized pseudowords that didn't follow L1 orthotactics did not show any effects of tDCS on translation accuracy (only reaction time facilitation) (Fiori et al., 2011). Given this, it's possible that acquisition requires some orthographic or phonological bootstraps for anodal tDCS to have an effect. However, this explanation does not appear to account for what appears to be an actual inhibition of learning in the anodal group (on the early N400).

An alternative explanation for the difference between the present study and the previous tDCS language learning studies focuses on the different tDCS systems used. Instead of the standard 5x7 cm^2 sponge anode and cathode electrodes as used in all three previous tDCS vocabulary acquisition studies, the present study used an HD-tDCS system consisting of a 4x1 ring configuration. HD-tDCS systems allow for more focal stimulation, as the four return electrodes can be adjusted around the center stimulatory electrode to target specific cortical depths and to constrain the electric field to the region within the 4 ring configuration (Caparelli-Daquer et al., 2012; Kuo et al., 2013; Edwards et al., 2013). However, a more focal stimulation may be problematic in that it could potentially miss much of the areas stimulated by the standard

5x7 cm^2 sponge electrode, which induces a large and diffuse electric field in the cortex. It is therefore likely that the stimulation in the present study was thus much more constrained to the LPSTG than previous studies, whose stimulation may have spread to other regions in the perisylvian language network such as the supramarginal gyrus (phonological processing of words) and angular gyrus (semantic processing) (Catani & Jones, 2005). It is possible, then, that the facilitatory effects of anodal tDCS on language learning is not due to BA22 as was in our study, but to BA22 in conjunction with other language regions in the proximity. In fact, our stimulation of BA22 may have interfered with L2 acquisition as shown in the smaller language learning effects in the anodal group compared to the sham group.

Combining these two properties of the present study (L2 word acquisition and focal stimulation), the learning inhibition seen in the anodal group may be due to facilitation of one aspect of language learning at the expense of others. Specifically, stimulation of BA22 is thought to improve lexical (word form) processing, particularly phonology (Floel et al., 2008; Price, 2000). L2 vocabulary acquisition requires not only establishing lexical forms (orthographic and phonological), but also the mapping of such forms onto semantics. Anodal HD-tDCS may have facilitated too much phonological activity during learning while other areas – like orthography and lexical-semantic mapping – are neglected. This emphasis could lead to the inhibition of overall L2 learning, manifested in the early N400.

5. Conclusion

The present study sought to test whether anodal tDCS was an effective means of facilitating L2 vocabulary acquisition. Behavioral results indicate no facilitation of learning due to anodal tDCS, in contrast to previous behavioral studies on tDCS and language learning. ERP results further revealed that anodal tDCS may in fact hinder L2 vocabulary acquisition as seen in the smaller learning effects in the anodal group compared to the sham group. Such a discrepancy between the present study and previous work may be due to the difficulty of L2 vocabulary acquisition as compared to L1-like pseudoword acquisition, differences in focal vs diffuse tDCS, or the combination of both.

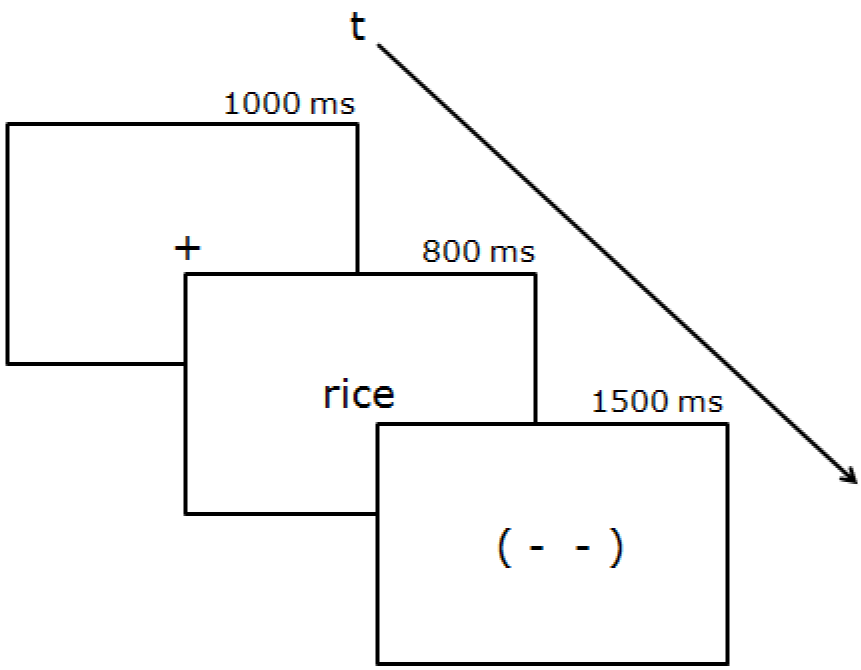

Figure 1: A critical trial in the English block of the go/no-go semantic categorization task

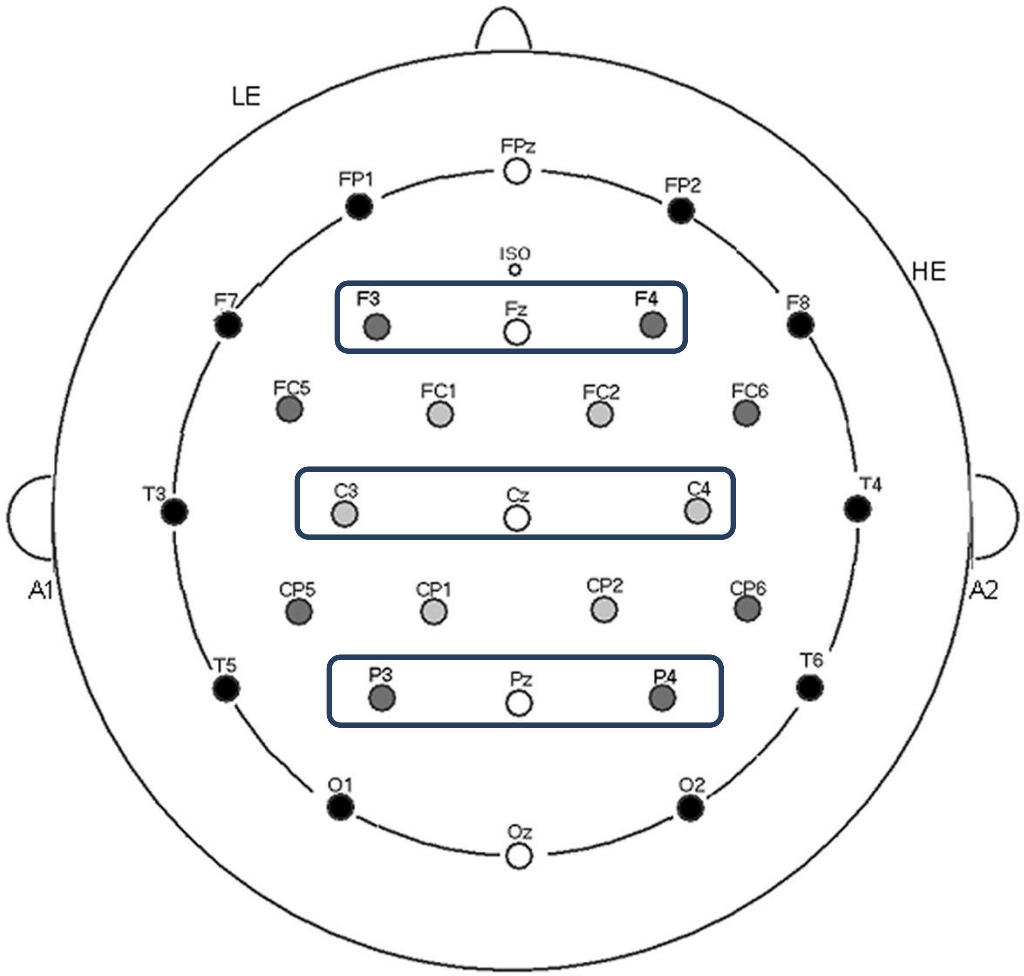

Figure 2: Electrode montage and electrode sites used for ANOVAs

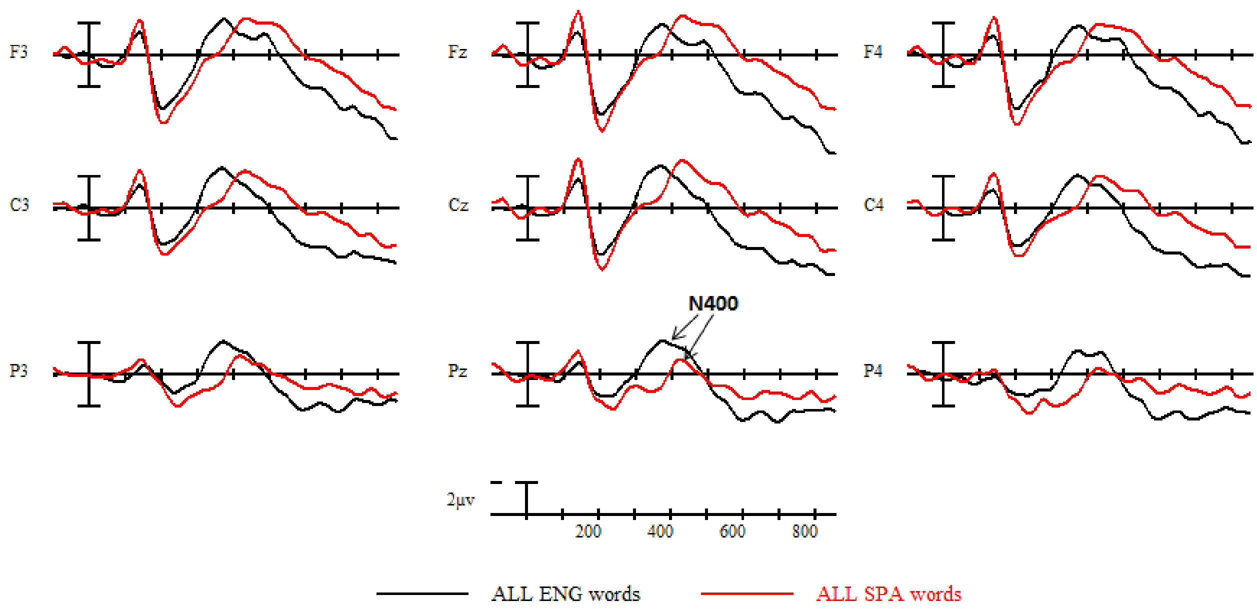

Figure 3: ERP Language effects from the nine electrodes sites used in ANOVAs

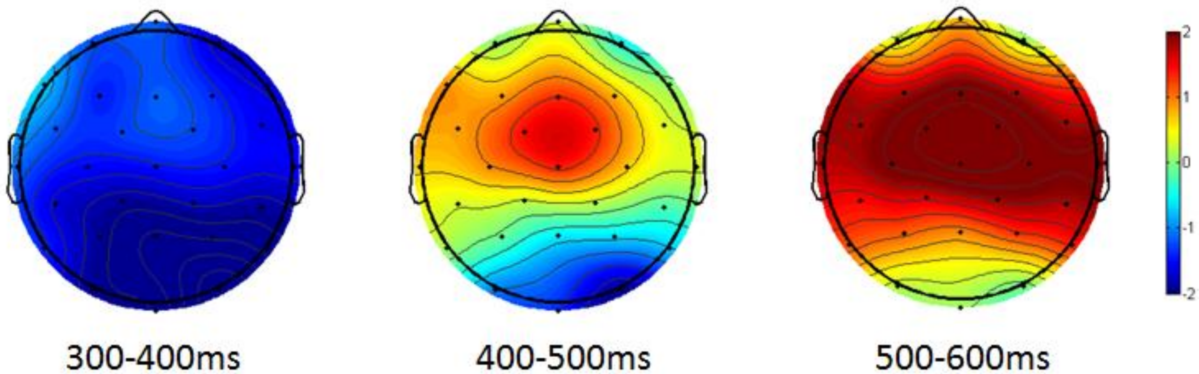

Figure 4: Voltage maps reflecting the language effects in 100 ms increments. These maps were created by subtracting the ERP waves to Spanish items from those of English items.

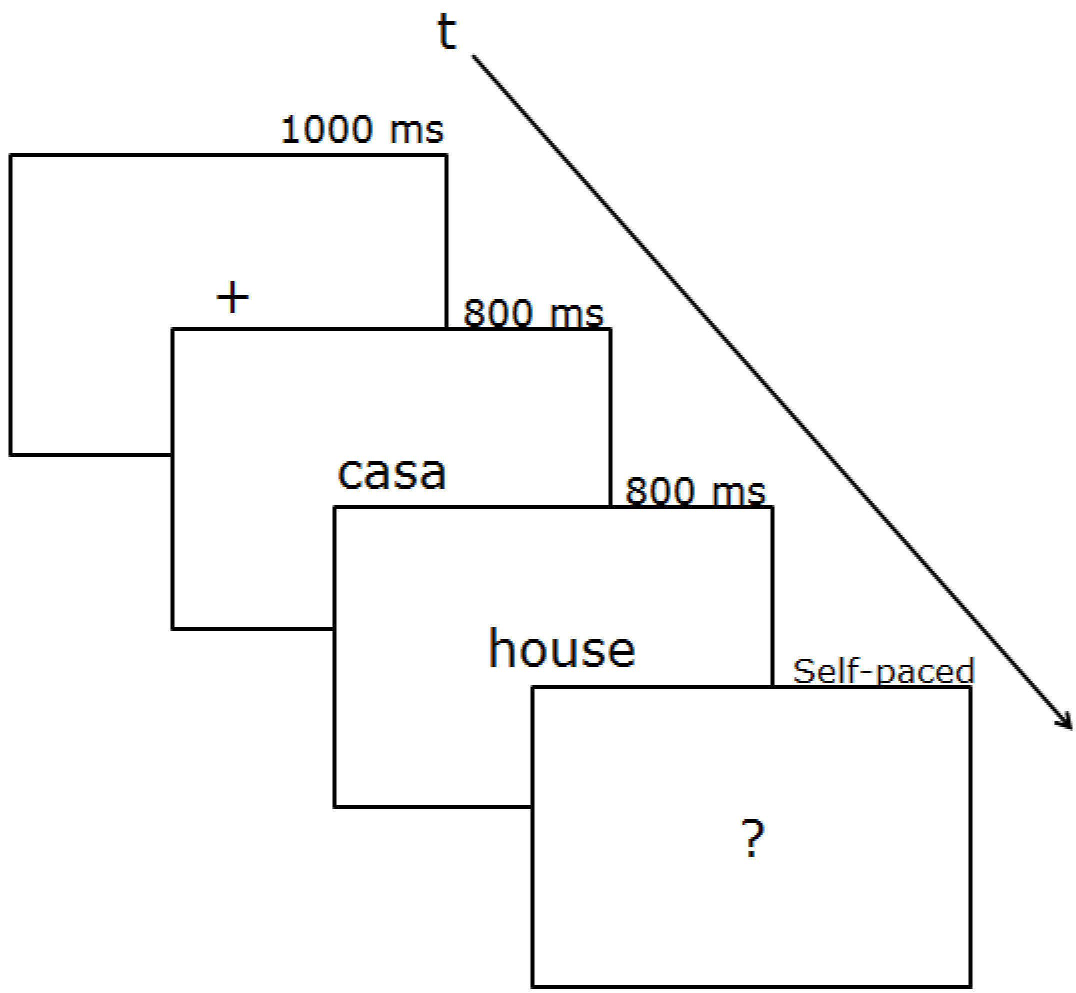

Figure 5: A critical ‘yes’ trial in the Yes-No Translation Task

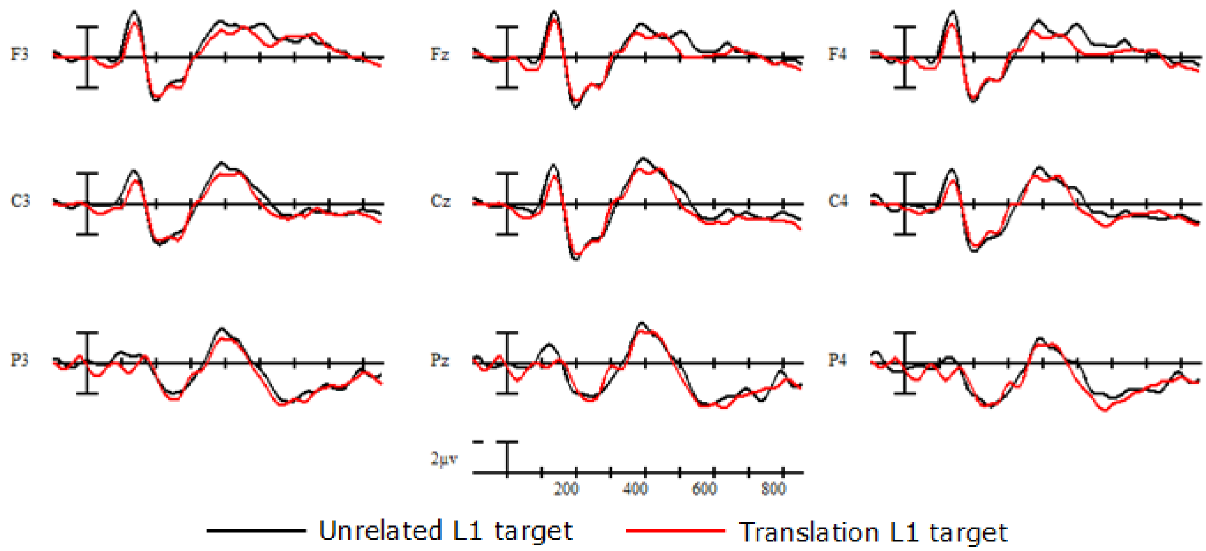

Figure 6: ERP translation priming effects before learning, from the nine electrode sites used in ANOVAs

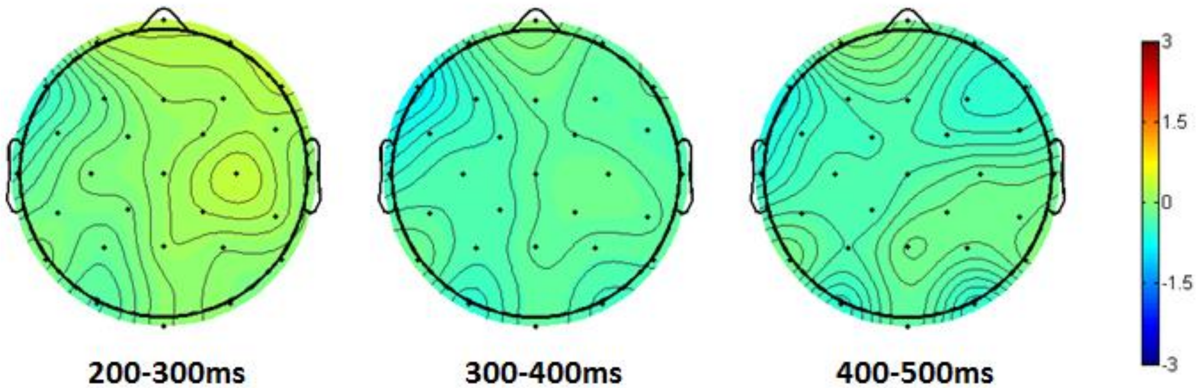

Figure 7: Voltage maps reflecting translation priming effects prior to learning in 100 ms increments. These voltage maps were created by subtracting the ERP waves to translation L1 words from those of unrelated L1 words.

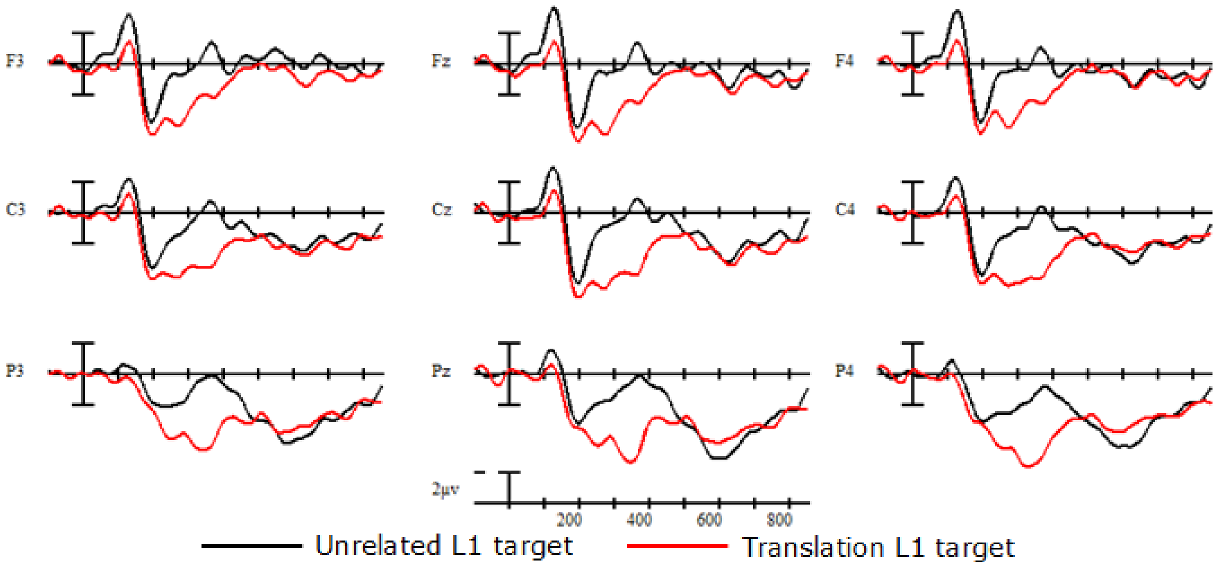

Figure 8: ERP translation priming effects after learning, from the nine electrode sites used in ANOVAs

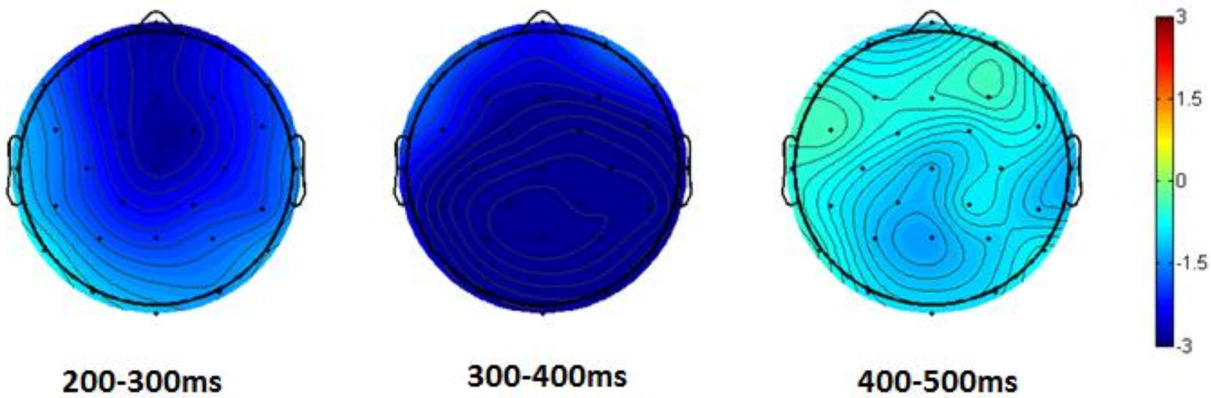

Figure 9: Voltage maps reflecting translation priming effects after learning in 100 ms increments. These voltage maps were created by subtracting the ERP waves to translation L1 words from those of unrelated L1 words.

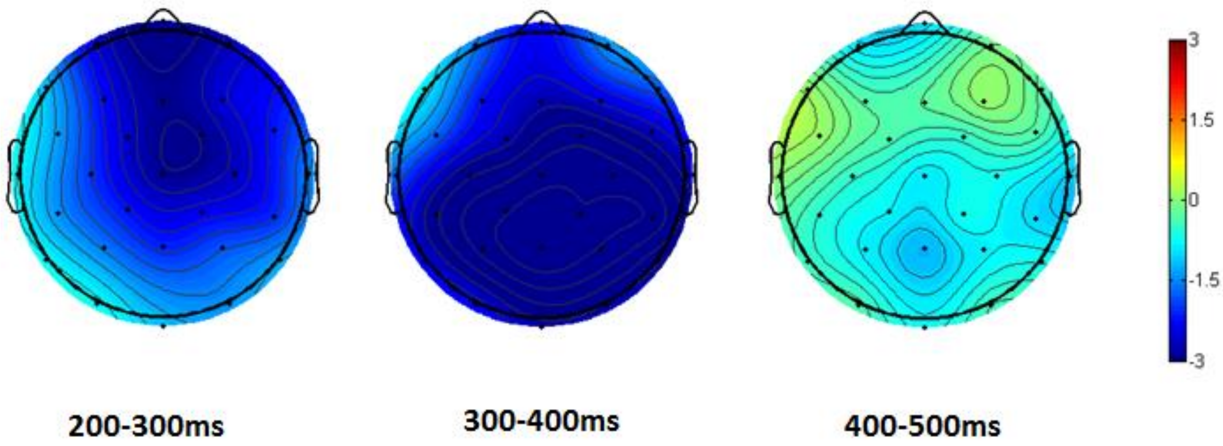

Figure 10: Voltage maps reflecting the change in translation priming effects due to learning. These voltage maps were created by subtracting the translation priming ERP difference waves of the first ERP session from those of the second ERP session.

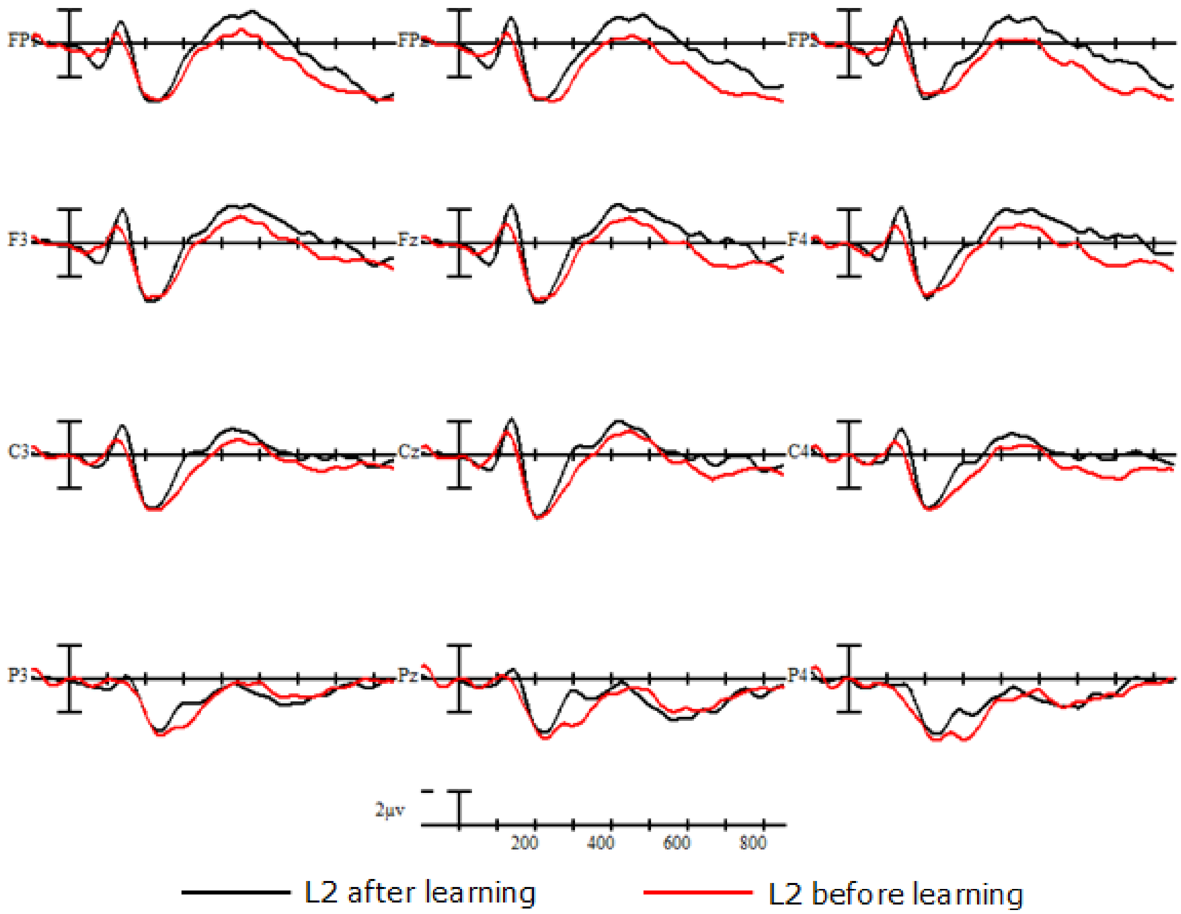

Figure 11: L2 word processing before (red) and after (black) learning, from the twelve electrode sites used in ANOVAs

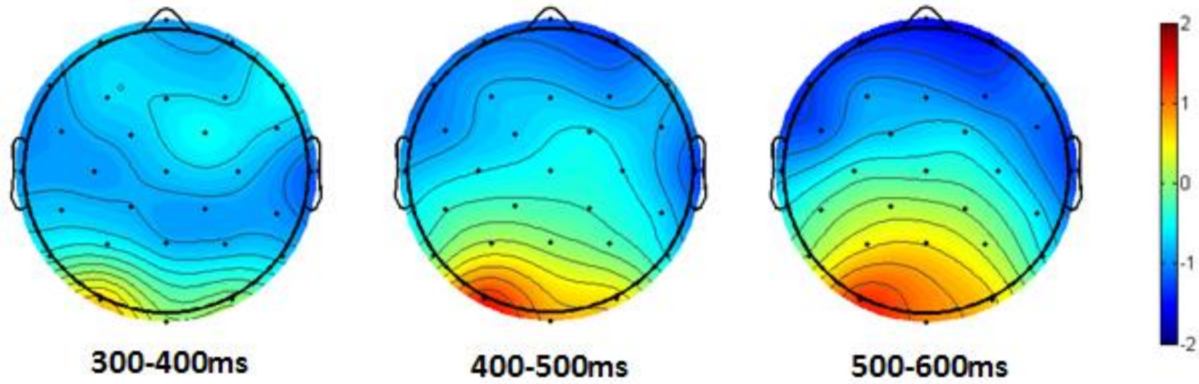

Figure 12: Voltage maps reflecting change in L2 processing between the first and second ERP session. These maps were created by subtracting the ERP waves to L2 words before learning from those after learning.

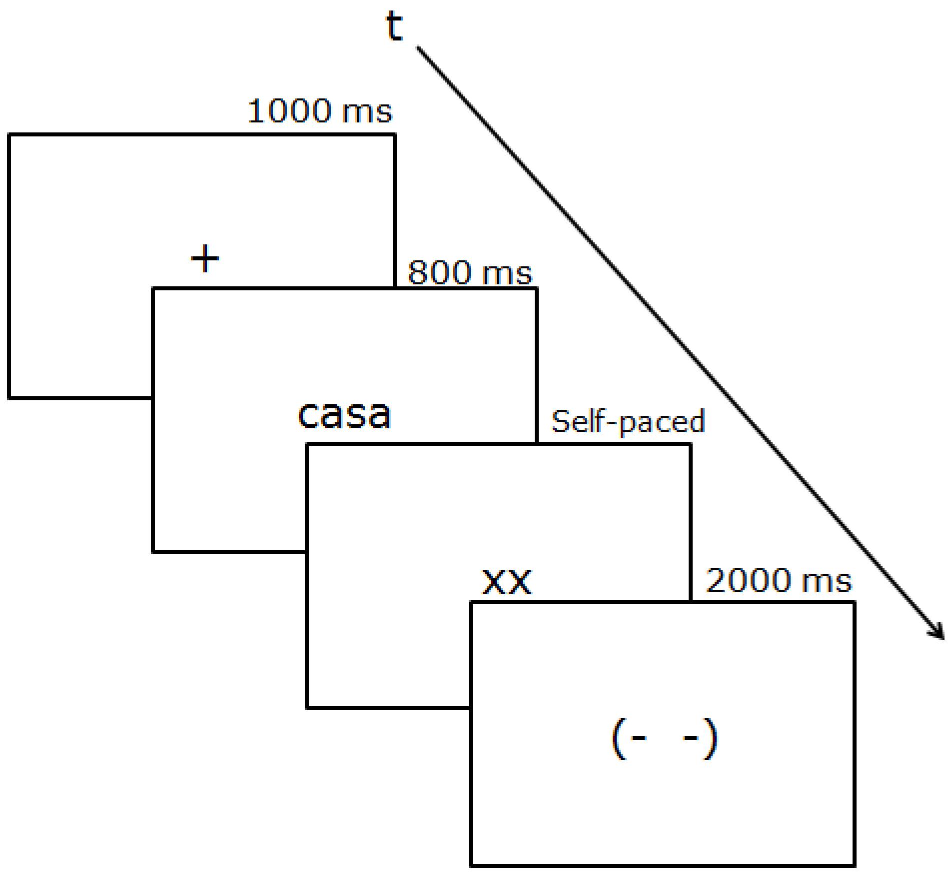

Figure 13: A critical trial in the Explicit Backward Direction Translation Task

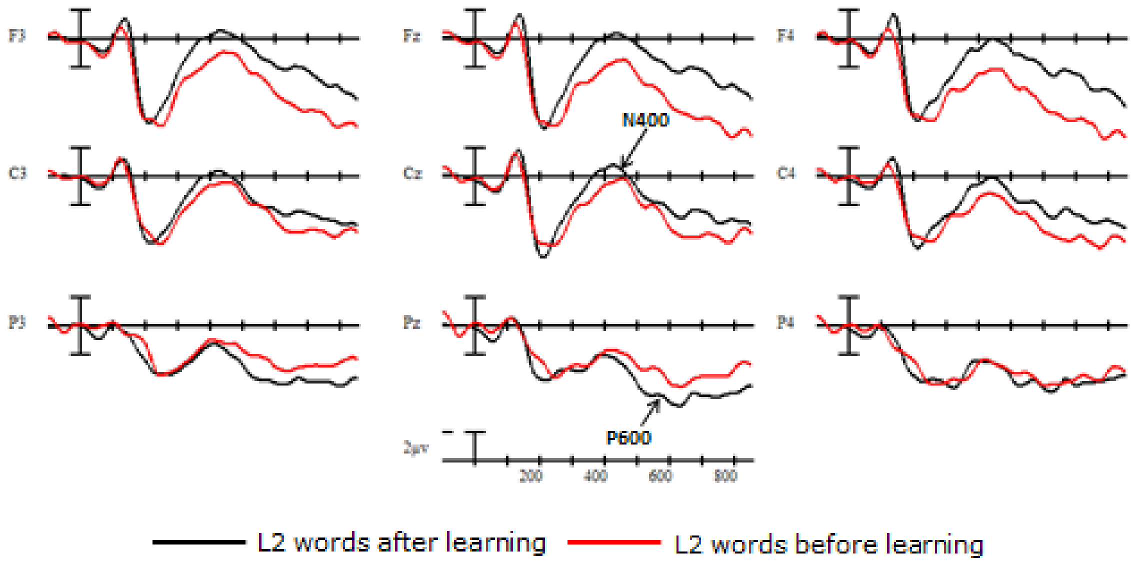

Figure 14: ERP effects of learning on L2 word processing in the sham stimulation group.

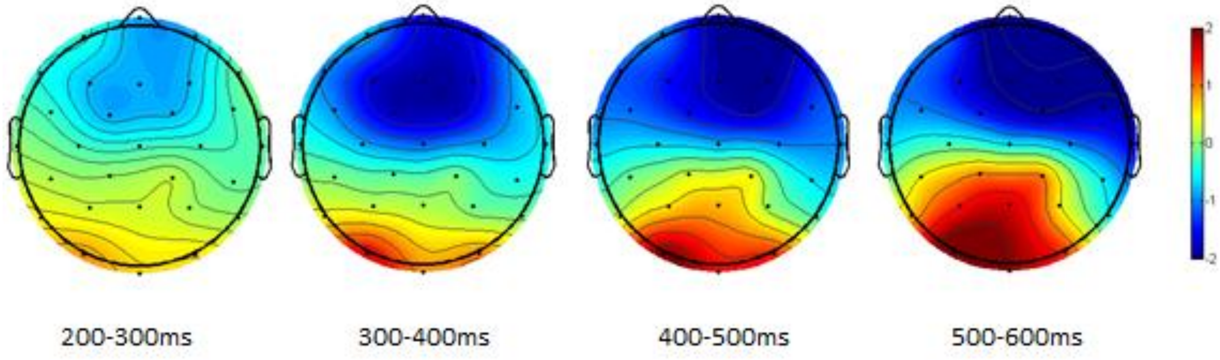

Figure 15: Voltage maps reflecting the change in L2 word processing due to learning in the sham stimulation group. These maps were created by subtracting the ERPs to L2 words before learning (first ERP session) from those after learning (second ERP session) for the 10 sham participants.

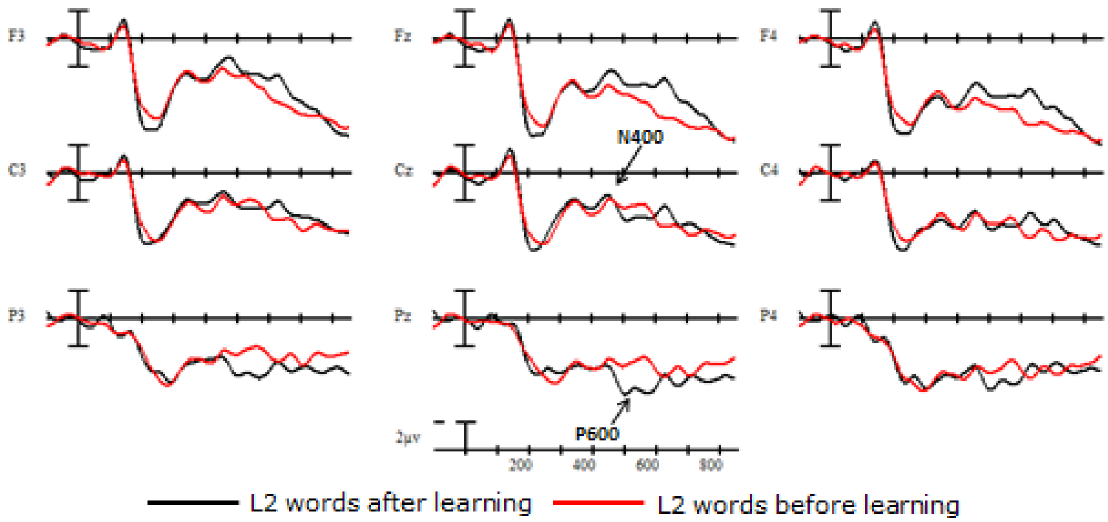

Figure 16: ERP effects of learning on L2 word processing in the anodal stimulation group.

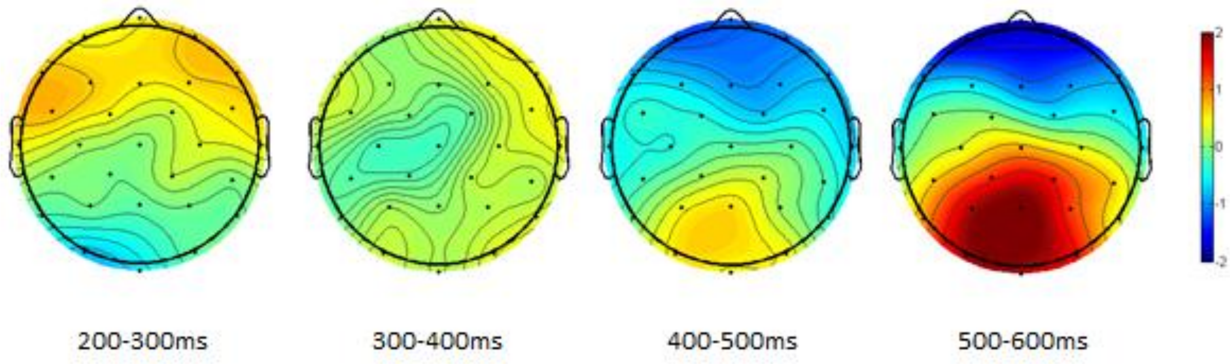

Figure 17: Voltage maps reflecting the change in L2 word processing due to learning in the anodal stimulation group. These maps were created by subtracting the ERPs to L2 words before learning (first ERP session) from those after learning (second ERP session) for the 10 anodal participants.

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