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Neural changes underlying early stages of L2 vocabulary acquisition

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ABSTRACT

Research has shown neural changes following second language (L2) acquisition after weeks or months of instruction. But are such changes detectable even earlier than previously shown? The present study examines the electrophysiological changes underlying the earliest stages of second language vocabulary acquisition by recording event-related potentials (ERPs) within the first week of learning. Adult native English speakers with no previous Spanish experience completed less than four hours of Spanish vocabulary training, with pre- and post-training ERPs recorded to a backward translation task. Results indicate that beginning L2 learners show rapid neural changes following learning, manifested in changes to the N400 – an ERP component sensitive to lexicosemantic processing and degree of L2 proficiency. Specifically, learners in early stages of L2 acquisition show growth in N400 amplitude to L2 words following learning as well as a backward translation N400 priming effect that was absent pre-training. These results were shown within days of minimal L2 training, suggesting that the neural changes captured during adult second language acquisition are more rapid than previously shown. Such findings are consistent with models of early stages of bilingualism in adult learners of L2 (*e.g.* Kroll and Stewart's RHM) and reinforce the use of ERP measures to assess L2 learning.

1. Introduction

Learning a second language (L2) is a critical step to succeeding in an increasingly linked world. In addition to the obvious communicative benefits of bilingualism, there has been some evidence suggesting a bilingual advantage in executive control across both linguistic and nonlinguistic domains (*e.g.* Bialystok, Craik, Green, & Gollan, 2009; but see Paap & Sawi, 2014 for an alternative view). Of particular importance 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; Luo, Luk, & Bialystok, 2010; Qian, 2002). Previous research using event-related potentials (ERPs) has shown L2 vocabulary acquisition to be accompanied by neural changes (McLaughlin, Osterhout, & Kim, 2004; Osterhout et al., 2008; Soskey, 2010; Yum, Midgley, Holcomb, & Grainger, 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

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track the neural changes during the earliest stages of L2 vocabulary acquisition in naïve learners who began to acquire vocabulary in an L2 and were tested within the same week.

When acquiring words in a new language, learners must first establish knowledge about word forms and then about word meanings. Evidence for this learning trajectory comes from McLaughlin et al.'s seminal study examining beginning 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 ERP effect after only 14 h of classroom instruction. Such lexicality effects have been interpreted in prior studies of first language (L1) to reflect the ability to differentially process known and unknown word forms (*e.g.* Holcomb & Neville, 1990). A semantic priming N400 effect, where learners show smaller N400 amplitudes to target words following related compared to unrelated prime words, manifested after 63 h of instruction, reflecting word meaning activation. This timing difference indicates that acquisition of word form knowledge precedes word meaning knowledge and suggests that a certain L2 proficiency threshold must be reached prior to any word meaning modulations of the N400. Importantly, learners showed these N400 effects in the absence of behavioral effects, indicating that ERPs can be a sensitive methodology for tracking early neural changes in L2 learners.

Models of L2 acquisition, such as the Revised Hierarchical Model (RHM) (Kroll & Stewart, 1994) and the developmental Bilingual Interactive Activation Model (BIA-D) (Grainger, Midgley, & Holcomb, 2010), have characterized this L2 vocabulary acquisition trajectory in adult learners. Specifically, both models propose that the earliest stage of adult L2 vocabulary learning is typically supervised and associative (*e.g.* learners of Spanish are explicitly told that '*cama*' means 'bed'). Learners thus acquire new L2 wordforms simultaneously with their L1 translation wordform activation, such that a strong L2 to L1 lexical link is established. This link leads to differential processing between L1 and L2 words in adult L2 learners, where L1 meaning access is direct while L2 meaning access is indirect/lexically-mediated. In other words, beginning L2 learners access L2 word meanings through their L1 translation wordforms, which are directly connected 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) (Kroll & Stewart, 1994).

ERP support for a stronger backward than forward connection in L2 learners comes from N400 translation priming effects in unbalanced bilinguals that show earlier effects in the L2 to L1 direction than in the L1 to L2 direction (Alvarez, Grainger, & Holcomb, 2003). This effect appears to be lexically mediated as predicted by both the RHM and BIA-D: subsequent findings in another group of unbalanced bilinguals show larger L2 to L1 than L1 to L2 N250 translation priming effects (Schoonbaert, Holcomb, Grainger, & Hartsuiker, 2011). The N250 component has been argued to reflect sublexical to lexical form mapping (Holcomb & Grainger, 2006). However, most asymmetric N400 translation priming effects in unbalanced bilinguals have been found in the opposite direction, with forward, rather than backward, translation priming leading to significant effects (for review, see Duñabeitia, Perea, & Carreiras, 2010). This asymmetry disappears in balanced bilinguals, with similar N400 translation priming effects in both forward and backward directions (Duñabeitia et al., 2010).

One explanation for such progression of translation priming effects is the development of L2 proficiency and its effects on meaning access. Both the RHM and BIA-D posit that as L2 proficiency increases, L2 meaning access becomes less reliant on the L1 system. In highly proficient bilinguals, L2 wordforms are directly connected to meaning and these connections are stronger than any lexical connections from L2 to L1 (Kroll & Stewart, 1994). The BIA-D extends this further by proposing that such a change is due to improved inhibition of L1 lexical representations during L2 processing (Grainger et al., 2010). Specifically, L1 and L2 translation wordforms develop inhibitory links between them as L2 proficiency increases, such that activation of an L2 word no longer activates its L1 translation wordform (Grainger et al., 2010; Grant, Fang, & Li, 2015). This development suggests that moderately proficient bilinguals are in a transitional stage of inhibiting L1 lexical translations during L2 processing, such that L2 to L1 lexical links are weakened while direct L2 to semantics links are strengthened. For balanced bilinguals, L2 to L1 connections are thus semantically mediated and are similar in strength to L1 to L2 connections. With regards to L2 to L1 connections, this progression thus posits that 1) low proficiency adult bilinguals demonstrate strong lexically mediated L2 to L1 processing, 2) moderate proficiency adult bilinguals demonstrate weaker lexically mediated L2 to L1 processing, and 3) balanced adult bilinguals demonstrate strong semantically mediated L2 to L1 processing. Put together, this can explain the different asymmetrical ERP translation priming effects seen across unbalanced bilinguals as well as the symmetrical effects seen in balanced bilinguals.

Focusing on the early stages of L2 vocabulary acquisition, the establishment of the aforementioned lexicosemantic networks can be directly captured by changes in the N400 component. In particular, the amplitude of the N400 grows as a function of L2 learning and can thus be used as a measure of L2 proficiency. Soskey found that learners who were enrolled in Introductory Spanish classes showed increasingly larger N400s to L2 words as the semester progressed (2010). Specifically, the smallest N400 was seen after 34 days of instruction and the largest after 153 days. Similarly, lab-based L2 learning has also elicited N400 growth as sessions advanced across 4 weeks (Yum et al., 2014). These findings indicate that the N400 component can be a useful tool for gauging L2 learning progression in both classroom and lab settings. As L2 proficiency increases, so should N400 amplitudes to L2 words. Importantly, N400 growth due to L2 learning reflects increased lexicosemantic processing rather than just L2 word repetition. Simple repetition of items predicts increases in the late positive component (LPC) and not the N400 (Nagy & Rugg, 1989). N400 amplitude changes to L2 learning therefore index lexicosemantic activity indicative of stronger L2 wordform representations and/or L2 lexicosemantic connections.

1.1. Present study

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 h of laboratory L2 vocabulary training in a single week. This amount is significantly less than any previous published report (including McLaughlin et al.'s 14 h findings, 2004). Our goal in testing for such early effects was to establish a marker for when N400 based lexicosemantic changes might occur during L2 learning. Although any behavioral evidence of L2 learning would imply a change in neural processing, it's not certain whether ERPs are sensitive to such changes after only a few hours of instruction. As McLaughlin et al. demonstrated, learners must reach a certain amount of L2 exposure before their L2 N400s are modulated by word meaning (2004). It is therefore important to characterize early learning effects: are they detectable and if so, how do they compare to previous effects in L2 learning (*e.g.* are the effects indicative of N400 or LPC changes) and how do they reconcile with models of early L2 vocabulary learning like the RHM and BIA-D? Additionally, detection of such early effects would inform efforts at improving L2 learning methods by allowing future studies to utilize ERP measures in assessing different teaching strategies.

With these motivations in mind, we tested for translation priming ERP effects in early stages of L2 learning using a backward (L2 to L1) translation recognition task in lab trained participants. We chose to test in the backward direction due to the predictions of strong L2 to L1 lexical connections during the early stages of L2 acquisition as informed by the RHM and BIA-D. Considering this, beginning L2 learners may more easily show observable effects in the backward than forward direction. Such findings would be line with Alvarez et al.'s demonstration of earlier and marginally larger backward than forward translation priming N400 effects in unbalanced bilinguals (2003).

Prior to and after lab-based L2 vocabulary learning, participants completed a translation recognition 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) backward translation priming effect before and after L2 learning and 2) changes to L2 word processing before and after learning. We were interested in examining both the N250 and the N400 components, previously shown to be modulated by translation priming (Alvarez et al., 2003; Midgley, Holcomb, & Grainger, 2009; Schoonbaert et al., 2011). According to the predictions made by the RHM and the BIA-D for learners in early stages of L2 vocabulary acquisition, we anticipated strong L2 to L1 connections that may manifest as observable backward translation priming effects after learning but not before learning. All previous ERP translation priming studies have utilized intermediate or higher proficiency bilinguals, making the present study the first to test for these effects at such an early stage of L2 learning. Additionally, our paradigm allowed us to test for changes in the N400 amplitude to L2 words. As in previous work demonstrating increasing N400 amplitudes 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 whether neural changes reported to occur after weeks or months of learning can also be detected after a few hours of learning.

2. Methods

2.1. Participants

Participants were 10 native English speakers (5 females; mean age = 21.3, SD = 3.4) recruited from Tufts University with no or limited exposure to Spanish or any other Romance languages. One participant reported having exposure to Spanish in elementary school 6 years ago, with no to little Spanish knowledge retained from the experience. Another two participants had minimal French exposure from introductory classes only. Prior to learning, participants reported no competency in Spanish in a Likert-scale language background questionnaire (1–7 where 1 = no skills and 7 = expert): 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 three of the participants who had limited Spanish or French exposure self-rated their Spanish proficiency with a 1 (no skill) across the aforementioned linguistic skills.

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 s). 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 and did not occur on the days of ERP testing (see *Procedure* for more details).

2.2. 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 ($t(99) = 6.63$, $p < 0.001$).

Our selection of 100 words to be learned was informed by previous work in lab-based L2 vocabulary acquisition (Liu, Dunlap, Fiez, & Perfetti, 2007; Yum et al., 2014). In Liu et al., 60 L2 words were successfully learned within one week across 3–4 days with a total of 6–7 h of training (2007). Yum et al. taught 200 L2 words for 4 weeks and noted changes in N400 after 10 days (2014). Note however that these previous studies utilized Chinese as the L2, which is more difficult for native English speakers to learn than same-script L2s such as Spanish. Our own pilot testing with L2 Spanish words found behavioral evidence of learning in a lexical decision task after four days of consecutive training within a week. In that pilot, we taught 95 words, informing a similar number for our current study.

Pronunciations of all 112 Spanish words were recorded in isolation by a female native Spanish speaker using a Sennheiser PC131 headset (80 Hz–15,000 Hz input). Each recording was edited using CoolEdit software (Johnston, 1999) to normalize for volume and onset latency, the latter ensuring that any silence or pauses in the spectrogram prior to word onset were removed.

2.3. Procedure

Participants completed four sessions throughout a single week: two ERP recording sessions and two vocabulary learning sessions (see Table 1). Each session started at the same time each day.

The first ERP session, recorded on Monday, provided the baseline neural signatures to L2 words prior to learning using a backward translation recognition task. At the end of this ERP session, we attained baseline measures of participants' knowledge of the 112 to-be-learned Spanish words on that day using an explicit backward translation task. On Tuesday and Thursday, participants completed a learning session consisting of our L2 learning protocol and a post learning translation assessment. Each learning session was completed in less than two hours. Finally, participants completed the backward translation recognition task again for the second ERP session on Friday, occurring one day after their second learning session. At the end of this ERP session, we again tested participants' knowledge of the 112 learned Spanish words using an explicit backward translation task.

2.3.1. Learning protocol

Participants engaged in two learning sessions, one on Tuesday and one on Thursday, during a single week. During the learning session, participants were trained on the 100 Spanish words and 12 Spanish body part probes using their corresponding English translations. Learning consisted of explicit association pairing of each Spanish word with its English translation (*e.g.* 'cama' – 'bed'). Using Qualtrics survey software, each word was shown for 4 s with a 2 s pound sign separating each pairing (Qualtrics, Provo, UT). Each pairing therefore took 10 s total (4 s Spanish presentation, 4 s English presentation, and 2 s pound sign). Participants also heard the pronunciation of each Spanish word simultaneously with their presentation on the screen. 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 recorded Spanish word took less than 1 s to play, giving participants 3 s to repeat it successfully. Multiple repetitions were discouraged to maintain similar amounts of Spanish exposure across participants.

Participants saw each Spanish-English pair twice per learning session: once in a forward association (L1 to L2) direction and once in a backward association (L2 to 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 and across the two learning sessions. For each list, participants had three timed 30-s breaks interspersed across the 112 pairs (one break after 28 pairs). In all, each learning session took roughly 1 h (25 min for each list).

Table 1
Participant schedule and tasks for the week-long experiment.

Monday	Tuesday	Wednesday	Thursday	Friday
ERP Session 1	L2 Learning 1	–	L2 Learning 2	ERP Session 2
Baseline recording of L2 word processing	*First learning session*		*Second learning session*	*Post learning recording of L2 word processing*
* Backward Translation Recognition Task	* Learning protocol		* Learning protocol	* Backward Translation Recognition Task
*Explicit Backward Translation Task	* Post Learning Translation Assessment		* Post Learning Translation Assessment	*Explicit Backward Translation Task

2.3.2. Post learning translation assessment

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 to L1) or the correct Spanish translation for one of the 112 English words seen in learning phase (forward translation, L1 to 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 (Kang, Gollan, & Pashler, 2013).

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.

2.3.3. Backward translation recognition 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 backward translation recognition task. During the task (see Fig. 2), participants held a gamepad and viewed a fixation cross at the center of the screen for 1 s 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. To create the list, we paired off 56 Spanish-English translations and then randomized the rest of the pairings such that they were incorrect translations of each other. Using the English words seen throughout the learning sessions, rather than new English words, for the incorrect pairings allowed us to compare translation English targets with unrelated English targets without concern that any translation priming effects were simply due to repetition. 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.

2.3.4. Explicit backward translation task

After both ERP sessions (baseline and postlearning), participants were asked to provide English translations to be learned/learned Spanish words. Participants viewed a Spanish word presented on the screen for 800 ms, followed by 'xx'. The 'xx' remained on the screen until the participant said aloud the English translation for the previous Spanish word. Participants were allowed to guess the translation or pass if they were unsure. Once they provided a response, the experimenter pressed a button signifying a correct or incorrect answer (unbeknownst to the participant) and the next Spanish word appeared on the screen. Participants saw all 100 to be learned/learned Spanish words during each session, with order randomized across sessions. Before the task, participants practiced translating a series of Spanish number words in order to familiarize them with the task.

2.4. EEG recording

For the yes/no translation 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 Fig. 1 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.

2.5. 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.

2.5.1. 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 100 ms intervals spanning 100 ms–500 ms post target onset allowed us to capture the effects of visually inspected early effects around the 100 ms, the N250 component (200–300 ms) and the N400

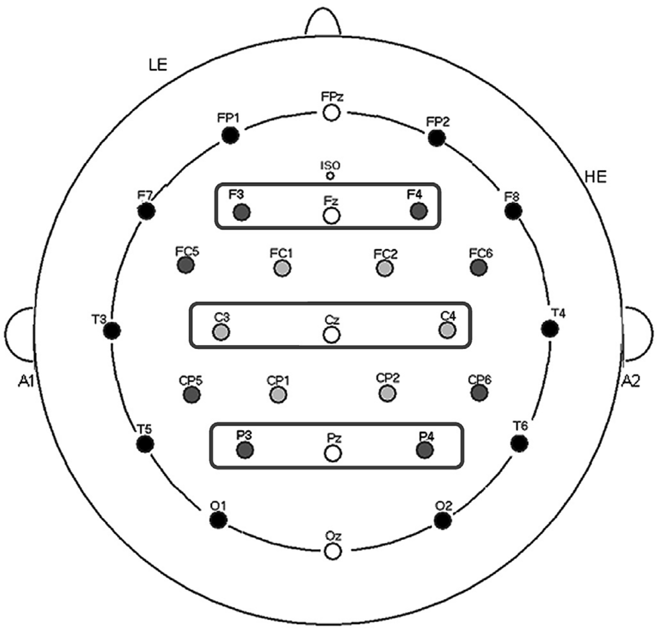

Fig. 1. Electrode montage and electrode sites used for ANOVAs.

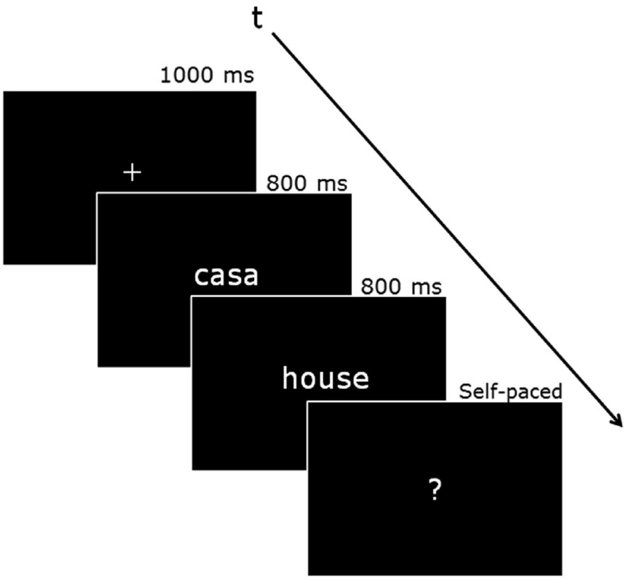

Fig. 2. A critical 'yes' trial in the Yes/no Backward Translation Recognition Task.

component (300–500 ms). 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 Fig. 1). 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 Greenhouse and Geisser (1959) correction.

2.5.2. 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 100 ms intervals spanning 300 ms–600 ms 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 Fig. 1). 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 Greenhouse and Geisser (1959) correction.

3. Results

3.1. Behavioral results

Across the two post-learning session translation tasks, participants chose the correct translation on average 95.9% of the time ($SD = 7.9\%$). For the yes/no translation task, participants had an average d' score of 0.44 ($SD = 0.39$) before learning. After learning, participants had an average d' score of 3.17 ($SD = 1.72$). These scores were significantly different, $t(9) = -5.09$, $p < 0.001$. On the explicit backward translation task, participants on average correctly translated 10% of the words before learning and 72.8% of the words after learning. These scores were significantly different, $t(9) = -9.55$, $p < 0.001$.

3.2. ERP results

3.2.1. Translation priming effect results

Fig. 3 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). Fig. 5 shows the same comparison after learning. The degree of translation priming after learning is captured in the voltage maps seen in Figs. 4 and 6, which were created by subtracting the translation L1 targets from the unrelated L1 targets. Fig. 4 displays the translation priming effect prior to learning and Fig. 6 after learning. Finally, Fig. 7 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.

100–200 ms epoch. No main effect of ERP session on translation priming size was found.

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 Figs. 4 and 6).

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 Figs. 4 and 6).

400–500 ms epoch. No main effect of ERP session on translation priming size was found.

3.2.2. L2 processing results

Fig. 7 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 Fig. 8.

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 Fig. 8).

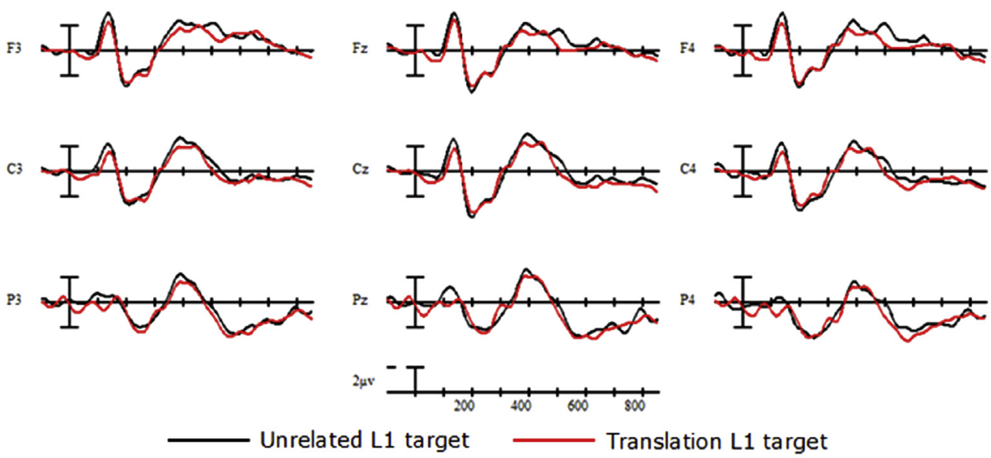

Fig. 3. ERP translation priming effects before learning, from the nine electrode sites used in ANOVAs.

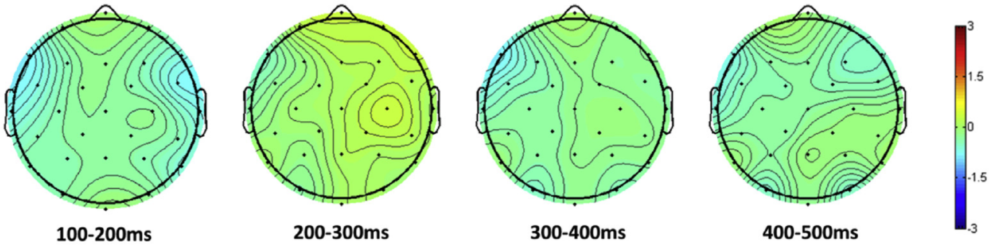

Fig. 4. Voltage maps reflecting translation priming effects prior to learning in 100 ms increments. These voltage maps were created by subtracting the ERP waves to translation L1 words from those of unrelated L1 words.

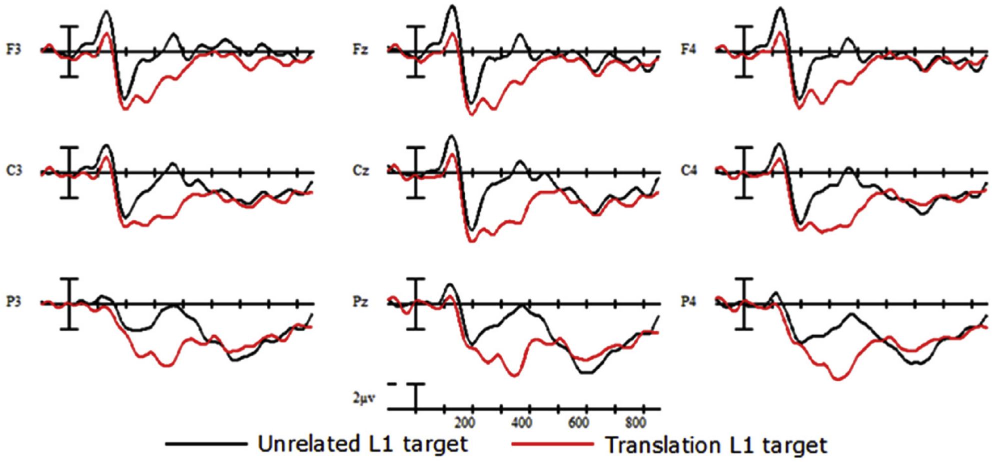

Fig. 5. ERP translation priming effects after learning, from the nine electrode sites used in ANOVAs.

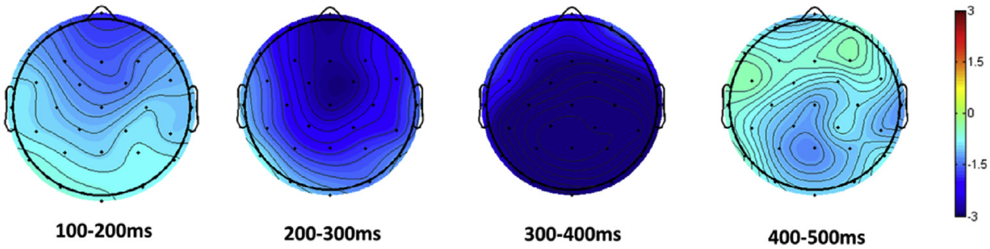

Fig. 6. Voltage maps reflecting translation priming effects after learning in 100 ms increments. These voltage maps were created by subtracting the ERP waves to translation L1 words from those of unrelated L1 words.

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 Fig. 8).

4. Discussion

In this study, we investigated the changes in the neurophysiological processing of L2 words in adult L2 learners who had less than 4 h of L2 vocabulary instruction. Specifically, we tested for the presence of backward translation ERP priming effects and L2 N400 changes after learning using a yes/no backward translation recognition task. This investigation was motivated by previous work showing ERP indices of L2 learning, with a focus on testing for how early these effects can be captured. Finding an N400 growth to L2 words after learning indicates increases in lexicosemantic processing, reflecting successful L2 vocabulary acquisition. Finding a backward translation ERP priming effect in these learners would also support the predictions

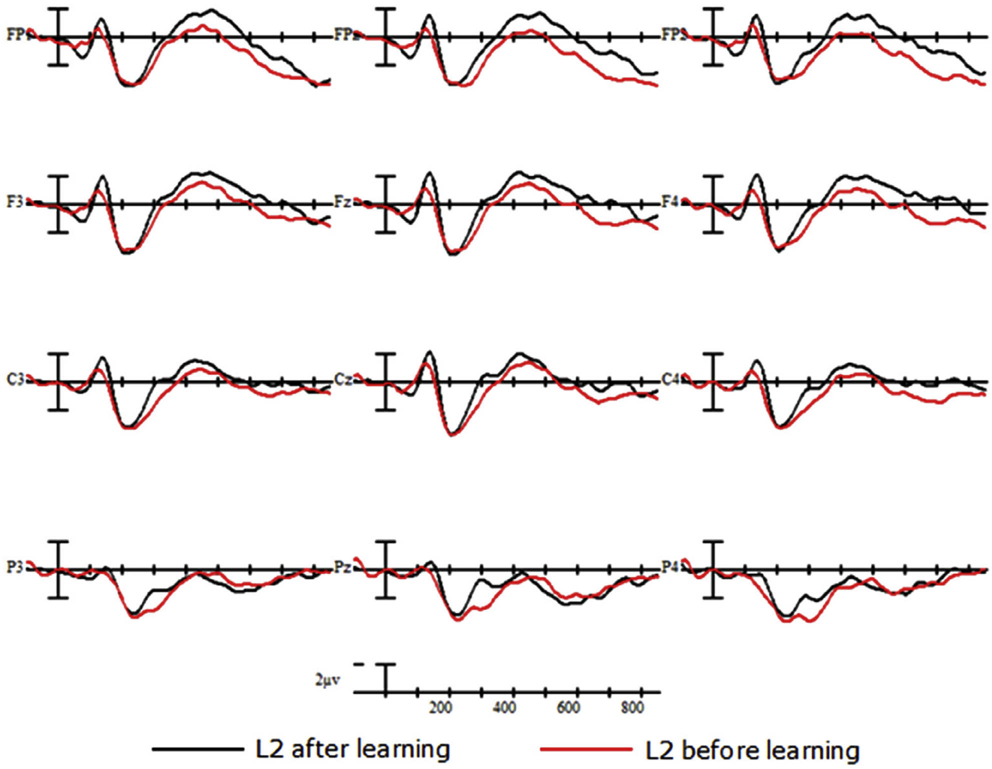

Fig. 7. L2 word processing before (red) and after (black) learning, from the twelve electrode sites used in ANOVAs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

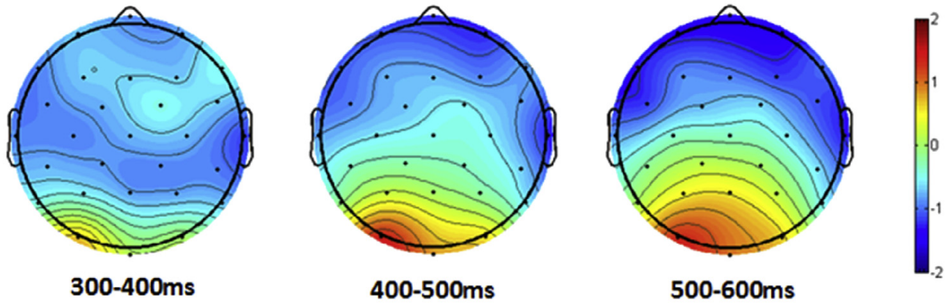

Fig. 8. Voltage maps reflecting change in L2 processing between the first and second ERP session. These maps were created by subtracting the ERP waves to L2 words before learning from those after learning.

of both the RHM and BIA-D models of bilingual processing, where strong, lexically mediated L2 to L1 connections are present during the early stages of L2 vocabulary acquisition. Such direction of effects have been absent in masked priming studies using moderate proficiency bilinguals (*e.g.* Midgley et al., 2009), perhaps reflecting the disengagement from the L2 to L1 lexical connection (Grainger et al., 2010).

Baseline translation results from the explicit backward translation task (10% accuracy on average) demonstrate that participants did not know most of the Spanish words to be learned. The two learning sessions were sufficient to induce behavioral measures of learning, as results 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. Additionally, participants performed better on the yes/no backward translation recognition task after learning than at baseline, as seen in the significant improvement in d' scores from the first to the second ERP session. Performance on the explicit backward translation task at the end of the second ERP also suggest that the two learning sessions were successful, as participants correctly recalled 72.8% of the Spanish word meanings. These significant effects of learning 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 (*e.g.* Yum et al., 2014).

Importantly, we were interested in the ERP effects of such learning. Would L2 N400s, reflecting establishment of L2 lexicosemantic networks, change as a result of learning? Would translation priming effects manifest in language ERP components after learning? Our task design (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. 4 relative to Fig. 6). 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).

4.1. *Backward translation priming effect*

Results 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 (Fig. 4 vs 6). This effect was robust from 200 to 400 ms, an early time-window for the N400 component. Previous studies using masked translation priming have shown clear N250 and N400 effects of backward translation priming in intermediate and proficient bilinguals (Hoshino, Midgley, Holcomb, & Grainger, 2010; Schoonbaert et al., 2011). 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. 5).

Additionally, visual inspection of the ERPs (see Figs. 3 and 5) revealed potentially early ERP translation priming effects at the N1/P150, where translation targets elicited more positive P150s than unrelated targets. However, this effect was not influenced by learning, shown by the lack of main effect of ERP session on the translation priming effect size from 100 to 200 ms. As the P150 has been hypothesized to reflect early letter/form processing, it is perhaps not surprising that we saw no learning effects, given that English (L1) and Spanish (L2) both use the Latin alphabet (Grainger et al., 2010).

The presence of a N400 backward translation priming effect in these early L2 learners supports the predictions of both the RHM and the BIA-D. 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 et al. (2009). In fact, studies showing stronger backward than forward translation priming effects have used relatively long prime durations, suggesting that perhaps conscious, strategic efforts may play a role (Alvarez et al., 2003; McDonough & Trofimovich, 2011; Schoonbaert et al., 2011). 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. Importantly, both interpretations reflect that backward translation is occurring in these adult L2 learners and such processes can be captured by ERP measures after only a few hours of learning.

4.2. *L2 processing changes due to learning - anterior N400s*

We discovered 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). Critically, N400 changes were found in the absence of LPC changes, indicating that this growth reflected changes in lexicosemantic processing and not just repetition effects (Nagy & Rugg, 1989). 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 et al. (2014). Recent work by Voss & Federmeier have argued that these anterior N400s – frequently labeled FN400s and thought to reflect familiarity – are functionally the same as N400s and are elicited during semantic processing (2011). Given these findings, we would argue that the anterior N400 changes captured in this study reflect the lexicosemantic network growth indicative of L2 vocabulary acquisition.

Importantly, our experiment showed this effect in the first week of learning after less than 4 h 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.

5. Future directions & conclusions

The present study explored the neural changes underlying the earliest stages of L2 vocabulary acquisition after only four hours of L2 instruction. Similar to effects shown in previous studies with intermediate bilinguals, our learners showed larger N400 components to L2 words following learning than at baseline. To our knowledge, this is the first study to show the presence of the translation priming effect in L2 learners with such minimal instruction. Previous ERP studies looking at translation priming have only utilized intermediate or proficient bilinguals (Alvarez et al., 2003; Midgley et al. 2009;

Schoonbaert et al., 2011). Our translation priming findings are consistent with models of bilingual processing such as the RHM and BIA-D. 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 neural changes that can be captured using ERPs.

Our findings also suggest that ERP measures can be used even in early stages of L2 acquisition to assess a quantifiable measure of learning beyond behavioral measures. Although we found both behavioral and ERP indices of learning, past research would suggest that ERP correlates of learning may be present even in the absence of behavioral evidence (McLaughlin et al., 2004). This suggests that similar ERP effects would likely have been seen with even less learning (*e.g.* if participants had less time dedicated to learning sessions). In future work, we would be interested in determining whether fewer exposures to new L2 words would result in a similar pattern of results.

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