CrossMark

Brain signatures of early lexical and morphological learning of a new language

Viktória Havas[a,b,*,1], Matti Laine[c], Antoni Rodríguez Fornells[a,d,e]

[a] Department of Basic Psychology, University of Barcelona, Passeig de la Vall d'Hebron 171, Edifici Ponent, 08035 Barcelona, Spain
[b] Department of Language and Literature, Norwegian University of Science and Technology, Dragvoll, Edvard Bulls veg 1, Bygg 5, 7048 Trondheim, Norway
[c] Department of Psychology, Åbo Akademi University, Fabriksgatan 2, 20500 Turku, Finland
[d] Cognition and Brain Plasticity Group, Bellvitge Biomedical Research Institute - IDIBELL, Barcelona, Spain
[e] Catalan Institution for Research and Advanced Studies, Barcelona, Spain

ARTICLE INFO

ABSTRACT

Morphology is an important part of language processing but little is known about how adult second language learners acquire morphological rules. Using a word-picture associative learning task, we have previously shown that a brief exposure to novel words with embedded morphological structure (suffix for natural gender) is enough for language learners to acquire the hidden morphological rule. Here we used this paradigm to study the brain signatures of early morphological learning in a novel language in adults. Behavioural measures indicated successful lexical (word stem) and morphological (gender suffix) learning. A day after the learning phase, event-related brain potentials registered during a recognition memory task revealed enhanced N400 and P600 components for stem and suffix violations, respectively. An additional effect observed with combined suffix and stem violations was an enhancement of an early N2 component, most probably related to conflict-detection processes. Successful morphological learning was also evident in the ERP responses to the subsequent rule-generalization task with new stems, where violation of the morphological rule was associated with an early (250–400 ms) and late positivity (750–900 ms). Overall, these findings tend to converge with lexical and morphosyntactic violation effects observed in L1 processing, suggesting that even after a short exposure, adult language learners can acquire both novel words and novel morphological rules.

1. Introduction

A fundamental aspect of learning a new language is the acquisition of its vocabulary. While word acquisition both in L1 and L2 has received considerable attention (e.g. Davis and Gaskell, 2009; López-Barroso et al., 2013; McLaughlin et al., 2004; Tamminen and Gaskell, 2013), there are only a few experimental studies on the acquisition of the building blocks of words, namely morphemes (Ferman et al., 2009; Havas et al., 2015; Merkx et al, 2011; Tamminen et al., 2015). To take a concrete example, each of the three morphemes that form the morphologically complex word *dance + r + s* carries distinct information that has to be recognized to grasp the full meaning of the word. Besides the semantic contents, morphemes and their combinations carry grammatical information, making the encoding of the internal structure of polymorphemic words essential for successful language learning. At the same time, there is extensive behavioural evidence indicating that acquisition of L2 inflection e.g. in subject–verb agreement, tense, and

gender marking is hard for adult second language learners (e.g. Hopp, 2010). In the present study, we examined the neurophysiological signatures of the earliest stages of lexical and morphological learning in adults acquiring a novel, artificial language. Previous experiments have mainly dealt with morphosyntactic agreement in L2 learners at different phases of their language training (Gillon Dowens et al., 2011; McLaughlin et al., 2010) or the acquisition of novel morphemes in L1 (Merkx et al., 2011; Tamminen et al., 2015). Here we examined the neural signatures of the earliest moments of incidental morphological learning of natural gender.

1.1. Morphosyntactic learning: previous neurophysiological evidence

Second language acquisition proceeds through different stages, and this has been argued to be the case also for morphological learning. For example, Zobl (1998) put forth a two-stage developmental model according to which language learning has two distinct phases based

---

on two psychological mechanisms: listing and computation. He claims that at early stage learners do not have access to functional, independent representations of affixal information. Instead, they store learned words individually as wholes without decomposition of their internal morphological structure. As they advance, the second, computational, stage emerges. At this stage, the learner masters the internal architecture of morphologically complex words.

The basic idea of two-stage learning of morphologically complex words appears compelling: at least during the first exposures to a novel morphologically complex word where both the stem and the affix(es) are unfamiliar, the learner should encode the word form as a whole. At issue here is if and when an adult learner becomes able to encode the constituent morphemes of novel multimorphemic words.

In a series of ERP experiments, McLaughlin et al. (2010) studied the different stages of morphological rule acquisition in learners of French, German and Finnish that were enlisted in university courses in these different languages. Each experiment targeted a different morphological or rule-based process (verb-noun number agreement in German, subject-verb number agreement and definite determiner and noun number agreement in French, and vowel harmony in Finnish). Nevertheless, a common pattern emerged: at a first stage of language learning (4 weeks to 12 months after the beginning of the language course), morphological violations elicited an N400 ERP component when compared to correct morphological forms. At later stages of language learning, participants with more training (either the same participants at a later stage or more advanced students) showed evidence for an L1-like processing in their second language where morphological violation elicited a P600 ERP component, taken to indicate that morphological processing took place. This led the authors to conclude that the grammatical rules of a second language can be mastered by adult language learners at a near-native level, but this process can take months or even years of training. Foucart and Frenck-Mestre (2012) found similar evidence in a noun-adjective gender agreement paradigm.

An ERP study by Weber-Fox and Neville (1996) found that the efficiency of morphosyntactic learning shows maturational constraints. For L2 syntactic violations, early anterior negativity was present in late but not early (10-year-olds or younger) L2 learners, being larger over the right than the left hemisphere. On the other hand, the late positivity (P600) was present in early learners, but showed increased latency for the 11–13-year-old group and was absent in participants who started L2 learning later in life. Lexical/conceptual violations, however, yielded a typical N400 negativity in all the age groups. In a different study, Hahne and Friederici (2001) tested a group of native Japanese speakers who had learned German as a second language after puberty and found a robust N400 effect for semantic violations, but no effect for syntactic violations in a sentence comprehension task. These results are in line with the declarative/procedural model by Ullman (2001) that assumes that the less efficient morphosyntactic learning by late L2 learners depends on their higher reliance on the declarative (lexical) memory system. At word level, reliance on the declarative system would mean that the late L2 learner employs full-form storage of multimorphemic words as opposed to L1 processing where decomposed representations of multimorphemic words are acquired with the procedural memory system.

However, Ullman's model was critiqued by Hahne et al. (2006) who found evidence for L1-like morphosyntactic decomposition for late L2 learners of German. Their adult L2 learners responded differently to violations of regular and irregular inflection during on-line morphological processing, eliciting LAN/P600 effects in the case of misapplications of regular rules of inflection and N400 effects in misapplications of irregular inflection. In other words, these results indicate that the participants employed regular rules of inflection in on-line morphological processing. There are also other studies that have found qualitatively similar ERP patterns of aspects of morphosyntactic processing in native speakers and highly proficient late L2 learners, with early

negativity followed by P600 (Dowens et al., 2011).

In summary, the ERP studies shortly reviewed above indicate that even adult learners can attain native-like on-line morphosyntactic processing skills if they reach a high level of proficiency in their L2. However, L2 learning in these studies has lasted from several weeks up to decades, and it remains open whether even a short exposure to a novel morphological rule can elicit neurophysiological responses indicative of morphological decomposition in adult learners.

1.2. Present study

The aforementioned studies reported a slow change in grammar-related neurophysiological responses during long-term L2 learning. However, there is also evidence suggesting that quick changes in language learning are possible. For example, Mestres-Missé et al. (2007) showed that new words produced ERP signatures similar to real L1 words after only three exposures when the meaning of the new word could be inferred from the context but not when the new word remained meaningless (for similar findings, see Borovsky et al., 2010; Dobel et al., 2009; Frishkoff et al., 2010). In the same vein, De Diego Balaguer et al. (2007) found evidence for fast ERP changes in a word and rule learning experiment where violation of syntactic-like rules in an artificial language produced a late positivity after only a four-minute exposure to the new language. These authors also found an N400 lexical effect during exposure to non-words vs. trained words shortly after training.

In a recent behavioural study (Havas et al., 2015) we used an incidental learning paradigm to examine morphological learning in an artificial language in adult Spanish and Finnish speakers (see Fig. 1). The participants were shortly exposed to pairs of novel words and pictures that they were instructed to learn. Part of the words carried an embedded morphological marker, namely a suffix that signalled the natural gender of the animate object they were paired with. Note that gender marking is absent in the L1 of Finnish speakers. The aim of the experiment was to see if a short exposure to morphologically complex words and their meanings enabled language learners to uncover the morphological rule embedded in the new language. Furthermore, we sought to study the influence of the morphological structure of L1 on L2 learning. Even though both groups were equally efficient in lexical learning (i.e., matching the word stems with the corresponding pictures), the Finnish speakers were better at discovering the hidden morphological gender rule and in applying that rule to novel lexical items presented after the learning phase. The group difference was quantitative rather than qualitative, as also the Spanish participants performed above chance in all experimental tasks, including the rule generalization task. This indicates that, at least under specific circumstances, adult language learners are able to quickly acquire morphological information from a new language even when the morphological feature in question is absent in their L1.

To investigate the neurophysiological correlates of the early stages of morphological learning, we applied our earlier paradigm (Havas et al., 2015) and shortly trained the present participants on novel words paired with pictures of either cartoon-like animals with prototypical female or male characteristics (targets) or with various animate and inanimate objects (fillers). The words paired with the animal characters contained a morphological regularity, namely a suffix marking natural gender, which the participants were not informed about. After a short training session, they were asked to come back a day later for testing. During the test phase we recorded EEG while the participants performed a recognition memory test and a rule generalization task to assess whether they successfully memorized the word-picture pairs (lexical learning) and to evaluate if they learned the gender rule (morphological learning). Based on earlier studies, we expected that successful acquisition of the embedded morphological rule would lead to early negativity (LAN) and/or late positivity (P600) in the case of violation of the gender rule. If, on the other hand, the participants
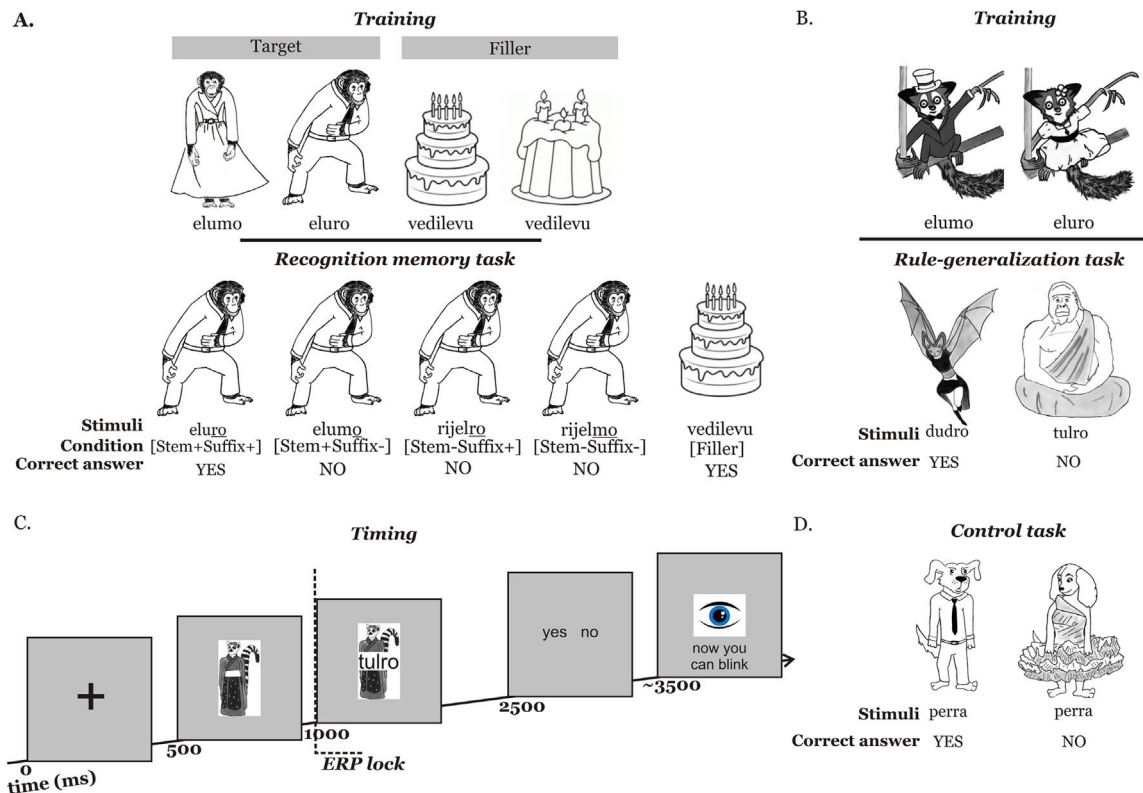
Fig. 1. [A] Examples of the stimuli of the recognition memory task, [B] rule generation task, [C] the timing of the ERP tasks and [D] L1 control task.

processed the novel word as a whole with no knowledge of the gender rule, we would expect an N400-like negativity when a non-matching word (incorrect stem, incorrect suffix, or both) is presented.

2. Methods

2.1. Participants

We tested 19 right-handed university students between the age of 19 and 34 (*M* = 22.37, *SEM* = .90, *SD* = 3.59). All participants were Spanish or Catalan speakers with normal or corrected to normal vision, and with no history of neural or psychiatric disorders or learning disabilities. The data of three participants had to be discarded due to technical problems with their EEG recordings.

2.2. Material

The to-be-learned training stimuli consisted of visually presented word-picture pairs (WPPs). The cartoon-like black-and-white pictures depicted both living and non-living objects (see Fig. 1). Part of the pictures (targets) depicted animals that had stereotypical Western male or female clothing/appearance while others were neutral in terms of gender (fillers). The picture names were pronounceable novel strings varying in length from 5 to 8 letters. In addition, the target names carried a gender marking in the form of a suffix. Two suffix pairs (mo-ro and za-ga) were employed, with both the pairs and their gender assignment counterbalanced across participants. For each object, two different pictures appeared in the training set. For the targets, these were the male and female variants of the same animal, and for the fillers visually somewhat different renditions of the same object (see Fig. 1). The fillers included both animate and inanimate objects.

Altogether 112 WPPs were created as training material. They consisted of 56 gender-marked WPPs (28 different animal species) and 56 fillers (28 pairs with two images per referent). To introduce variability to the novel strings, the word stems were constructed so that

seven stems had 3 letters (CVV, 2 × CVC, 2 × VVC and 2 × VCV), seven stems had 4 letters (2 × CVCV, 2 × VCVC and 3 × VCCV), seven stems had 5 letters (4 x CVCVC and 3 × CVCCV) and seven stems had 6 letters (2 × CVCVCV, 1 × VCVCVV, 2 × VCVCVC and 2 × CVCCVC). All novel words were phonotactically legal in Spanish.

2.3. Procedure

As previous studies have shown that off-line consolidation can affect the processing of newly learned words (Dumay and Gaskell, 2007; Tamminen et al., 2010), the experiment was completed on two separate days. On the first day, the participants completed the training phase that lasted about an hour and a half. Twenty-four hours later they returned for the test phase where they performed a recognition memory, rule-generalization and L1 gender violation task[2] during EEG recording and completed a final interview concerning their learning of the artificial language. The test session on the second day lasted about 2 h.

To avoid blinking during the presentation of the target stimuli, we designed the following trial structure that we used for the three tasks described below. First a fixation cross was shown in the middle of the screen for 500 ms. After that the target picture appeared for 500 ms in isolation, followed by the target word that appeared on top of the picture. Both stimuli stayed on the screen for 1500 ms, followed by a response cue that prompted the participant to answer. After either the response or the 2700 ms time limit, a new screen with an icon depicting a picture of an eye appeared for 2000 ms, allowing the participant to blink and prepare for the next trial. In data analyses, the event-related potentials were time-locked to the presentation of the target word.

---

[2] In this paper we focus on the morphological learning tasks; the L1 gender-violation task will be reported in a separate article. The L1 task was always performed last, therefore it could not interfere with the results of the tasks reported here.

2.3.1. Training

During the training phase, the participants were simply instructed to memorize as many of the 112 WPPs as possible. The WPPs were presented on a computer screen against a gray background with the words written in black. Each WPP was shown for 3500 ms with a 500 ms blank interval between the WPPs. The complete list of the 112 WPPs was presented eight times with a brief pause after every 16 WPPs. The presentation order of the WPPs was randomized for each presentation round, separately for each participant. The training task took about 80 min.

2.3.2. Recognition memory task

In this task, the participants were presented with WPPs. They were to press the left mouse button if the word and the picture matched and the right mouse button if the word and the picture did not match. In a factorial design, we devised stimuli where (i) both the stem and the suffix matched with the picture, (ii) only the stem or (iii) only the suffix matched, or (iv) neither morpheme matched. In addition, we included filler items in the stimuli. Examples for the different conditions can be seen on Fig. 1A. The purpose of this setup was twofold: first, the participants' ability to separate fully correct WPPs vs. fully incorrect WPPs gave a measure of overall word learning ability that did not hinge upon morphological learning; second, the participants' performance on the different types of incorrect WPPs was expected to show whether morphological learning had taken place. Previous evidence from a similar word-picture matching task with familiar word forms indicates that the word stem is the primary element in the meaning analysis of a suffixed word (Laine et al., 1999; Lehtonen et al., 2014). Accordingly, of particular interest was the participants' performance on items where the word stem matched the picture but the gender suffix did not. A participant who had learned the word but failed to acquire the meaning of the gender suffix would rely on the primary element (i.e., the stem) and thus be prone to incorrectly reply "yes" to such an item. In contrast, a participant who had learned also the meaning of the gender suffix should be able to reject such an item, albeit with a longer decision latency as the saliency of the matching stem makes the decision more difficult (Laine et al., 1999).

This design also allowed us to look at the specific electrophysiological brain responses to stem and suffix processing. In other words, we could tease apart these two components to identify their online processing differences.

The task comprised 336 trials divided into the five trial types: gender marked pictures with correct stem and correct ending (Stem +Suffix+; n =56), gender marked pictures with correct stem and incorrect ending (Stem+Suffix-; n=56), gender marked pictures with incorrect stem and correct ending (Stem-Suffix+; n=56), gender marked pictures with incorrect stem and incorrect ending (Stem-Suffix-; n=56), filler pictures with correct names (n=112) (see Fig. 1). This gave a total of 168 "yes" (left mouse button) responses and 168 "no" (right mouse button) responses. All pictures, stems, and suffixes presented were part of the training stimuli. All stimulus groups were also counterbalanced regarding the correctness of the WPPs.

2.3.3. Rule generalization task

This task evaluated the participants' ability to generalize the novel gender marking system to new stems. The participants were presented with completely new pictures (56 gender marked pictures depicting 28 animal species) and letter strings so that each picture was coupled with one string that had the same stem+suffix structure as the target words in the training set. The stem was always a letter string participants had not seen previously, while the suffix was the gender marker used in the training set (see Fig. 1 for an example). The gender suffix matched the cartoon animal's gender in half of the WPPs. By pressing the corresponding button, the participant was to decide whether the word matched the picture. The participants were not informed about the gender rule at this point either, but were simply told to use their own

criteria to respond.

2.3.4. Interview

Following the completion of the L1 gender violation task, the participants were asked a few short questions concerning their explicit knowledge of the gender marking system embedded in the WPPs. The participants scored from −1 to 3 depending on their explicit awareness of the gender marking rule. To get the highest score of 3, the participant had to spontaneously report the gender marking rule on the general question "How would you describe this language?" If the participant did not report the rule, the second question "Have you noticed any regularities in this new language?" was asked and the participant was awarded 2 points if the gender marking system was described at this point. If the participant still did not report the morphological rule, the third question "Were certain words, or parts of words, more common than others?" was asked. At this point, the participant was awarded 1 point for reporting the gender marking system. If the participant did not report the specific word endings after the three questions, a sheet with 6 consonant-vowel pairs (MO, GA, ZA, PE, RO, TI) was presented and they were asked to point to the consonant-vowel pair/pairs they thought to be the most common one/ones in the training material. For each correct response, .25 points was awarded, while .25 points was subtracted for each incorrect response. Thus the total score ranged between −1 and .5 points.

2.4. EEG recording and data processing

The electroencephalogram (EEG) was recorded from the scalp using tin electrodes mounted in an elastic cap (Electro-Cap International), located at 29 standard scalp locations (Fz, Cz, Pz, Fp1/2, F3/4, Fc1/2, C3/4, Cp1/2, P3/4, O1/2, F7/8, FC5/6, T3/4, T5/6, Cp5/6, PO1/2), and referenced on-line to the right ocular canthus. All scalp electrodes were referenced off-line to the average of both mastoids. Vertical eye movements were monitored with an electrode below the right eye (vertical EOG). All electrode impedances were kept below 5 kOhm. The electrophysiological signals were filtered with a bandpass of .01–70 Hz (half-amplitude cutoffs) and digitized at a rate of 250 Hz. The trials in which base-to-peak electrooculogram (EOG) amplitudes exceeded 75 μV, amplifier saturation occurred, or the baseline shift exceeded 200 μV/s were automatically rejected off-line; the mean percentage of rejections was 9.9%. EEG recordings of both tasks were pooled together before averaging the data for the different conditions. All clean trials in each condition (max. 112 trials for the fillers and 56 for all other conditions) were included into these averages. The EEG signal was averaged separately for each condition for epochs of 1024 ms including a 100 ms prestimulus baseline before the onset of the target word or non-word.

After visual inspection of the average waveforms of the correct and rule-violation conditions of all three tasks, we chose three time windows for the analysis of the recognition memory task: 250–350 ms to assess the early negativity, 350–450 ms for the N400 negativity and 450–600 ms to study the late positivity effect (P600). Furthermore, we chose one time window for the rule-generalization test (250–400 ms) to assess early positivity, and one for the control task (350–500 ms) to assess the N400 effect. These time-windows are within the expected time ranges of the N200 (Folstein and Van Petten, 2008; Nieuwenhuis et al., 2004), the N400 (Frenzel et al., 2010; Morris and Holcomb, 2005; Proverbio and Riva, 2009; see Kutas and Federmeier, 2011 for review), and the P600 (Dowens et al., 2011; Frenzel et al., 2010; Mehravari et al., 2015; Morris and Holcomb, 2005) component, respectively. We used repeated measures analyses of variance to assess the effects of experimental conditions and electrode locations. Even though all ERP waveforms shown in the figures were digitally filtered using a low-pass filter with a 9 Hz half-power cutoff, the statistical analyses were computed with the unfiltered data. For all statistical effects involving two or more degrees of freedom in the numerator, the

Huynh-Feldt epsilon was applied, the exact p-values after correction are shown in the results. Since we examined three time windows in the recognition memory test, a multiple-comparison correction was applied by setting the alpha level at p < .017 and considering p < .04 as marginally significant.

To evaluate the different effects encountered we conducted repeated measures ANOVAs in the corresponding time-windows selected. We used a configuration of 9 electrodes (F3/C3/P3/Fz/Cz/Pz /F4/C4/P4) for studying the possible differences in topographical distribution of the effects observed, including the following within-subject factors: Laterality (3 levels - left, central, right) and Anterior-Posterior locations (3 levels - anterior, central, posterior). We chose this distribution based on the visual inspection of the scalp distribution of the effects evaluated and also considering previous ERP studies on morphological processing (Münte et al., 1999; Rodríguez-Fornells et al., 2001; Soveri et al., 2007). In these studies, more lateral temporal and parieto-occipital locations are included in the ANOVAs because the strong lateralization of some of the components associated to morphological violations. However, in the present case, the selected locations at central and parasagittal lines, from anterior (frontal) to posterior (parietal sides) were able to cover all the ERP effects shown in the present study (see below in the corresponding figures the topographical maps).

3. Results

3.1. Behavioural results

3.1.1. Recognition memory test

The level of accuracy of the Stem + Suffix + condition (M = .84, SD

Table 1
The mean values, standard error of mean and standard deviation of the d-prime values of the Stem + Suffix-, Stem-Suffix + , and Stem-Suffix- conditions of the recognition memory task.

Recognition memory	M	SEM	SD
Stem + Suffix-	1.547	.332	1.326
Stem-Suffix +	2.012	.277	1.109
Stem-Suffix-	2.741	.324	1.310

= .11, *SEM* = .03) and the Filler condition (M = .97, SD = .05, *SEM* = .01) indicate that the participants were able to learn the WPPs efficiently. One-sample *t*-tests showed that all of the conditions had a significantly higher accuracy rate than chance, *t*(15) > 4, *p* < .001, except for the Stem + Suffix- condition (words with stems that match the picture but with the wrong gender suffix) where the participants had difficulties rejecting the items, *t*(15) = 1.74, *p* = .101; accuracy rates are depicted in Fig. 2A.

We calculated the d-prime values for the Stem + Suffix-, Stem-Suffix + and Stem-Suffix- conditions using the Stem + Suffix + accuracy rates as hits for all three conditions, while false alarms were the incorrect responses in the conditions Stem + Suffix-, Stem-Suffix + and Stem-Suffix- condition respectively (see Table 1 for the group average values). A one-way repeated measures ANOVA on the d-prime values with the factor condition (3 levels - Stem + Suffix-, Stem-Suffix + and Stem-Suffix-) revealed a significant overall difference between these conditions, *F*(2, 30) = 12.01, *p* = .0001, η^2 = .446. Post-hoc analysis with a Bonferroni correction showed a statistically significant difference between the Stem-Suffix- condition and the other two conditions
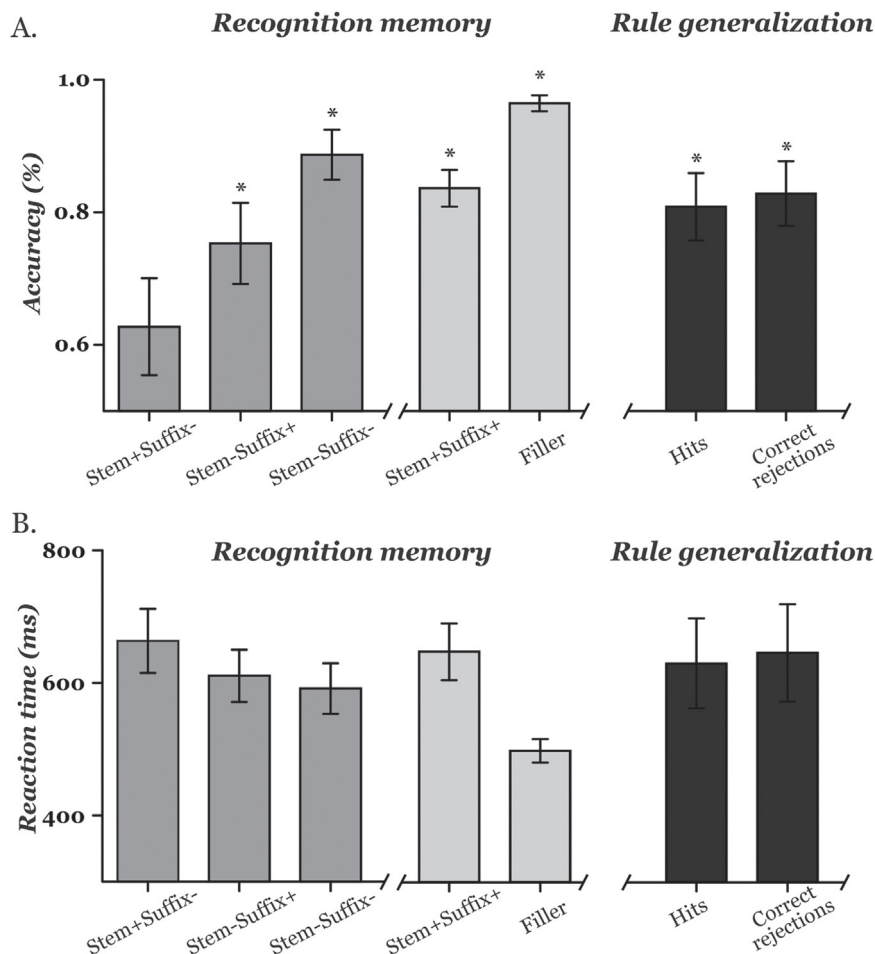

Fig. 2. Accuracy as expressed by percentage of correct responses [A] and reaction times in ms [B] per task and condition. Error bars represent standard error of mean.

($p < .01$). Even though we did not find a significant difference between the Stem + Suffix- and Stem-Suffix + conditions ($p = .4$), trend analysis showed that the three levels of the factor condition were distributed in a linear fashion, $F(1, 15) = 26.76$, $p = .0001$, $\eta^2 = .641$.

A one-way ANOVA on the reaction times with the factor condition (3 levels - Stem + Suffix-, Stem-Suffix + and Stem-Suffix-) showed a significant effect of condition, $F(2, 30) = 6.93$, $p = .007$, $\eta^2 = .331$. Post-hoc tests revealed a significant difference between the Stem + Suffix- conditions and the Stem-Suffix- condition ($p = .013$) so that the Stem + Suffix- responses were slower. All other comparisons were non-significant ($p > .1$). As was the case with accuracy, we found a statistically significant linear trend between the conditions, $F(1, 15) = 11.46$, $p = 004$, $\eta^2 = .45$ (see Fig. 2B).

3.1.2. Rule generalization task

The rule generalization test showed that most participants were able to learn the gender rule and transfer that knowledge to new items. The mean accuracy rates of both hits and correct rejections were above .8 (hits: $M = .81$, $SD = .20$, $SEM = .05$; correct rejection: $M = .83$, $SD = .19$, $SEM = .05$). Fig. 2A and B show the average accuracy rates and the RTs on the task.

3.1.3. Interview

The interview conducted after the experimental tasks showed that most participants were aware of the hidden morphological rule in the new language. While the interview scores could range from −1 to 3, the group average was 1.94 ($SEM = .20$, $SD = .81$) indicating a good level of learning and awareness. We have also found a statistically significant correlation between the interview scores and the d-prime values of the rule generalization test $R^2 = .747$, $p = .001$ indicating that

Table 2
The F-values of the repeated-measures ANOVA of the recognition memory and rule generalization tasks.

Recognition memory	250–350 ms	350–450 ms	450–600 ms	df
stem	2.31	7.77[*]	.05	1, 2
suffix	1.83	.33	12.03[*]	1, 2
stem x suffix	5.94[#]	2.95	.73	1, 2
stem x lat	9.84[*]	8.33[*]	8.00[*]	2, 30
stem x ant-post	.04	1.46	.20	2, 30
stem x lat x ant-post	2.57[#]	5.18[*]	5.69[*]	4, 60
suffix x lat	.71	2.19	1.75	2, 30
suffix x ant-post	7.15[*]	1.57	3.06	2, 30
suffix x lat x ant-post	.61	.73	.29	4, 60
stem x suffix x lat x ant-post	.17	.29	.18	4, 60
Rule generalization	250–400 ms	750–900 ms		
accuracy	11.09[*]	7.87[*]		
accuracy x lat	.07	1.35		
accuracy x ant-post	.19	2.24		
accuracy x lat x ant-post	1.41	.42		

[*] $p < .017$.
[#] $p < .04$.

participants who performed well on the rule generalization task were most probably aware of the gender rule.

3.2. ERP results

3.2.1. Recognition memory test

Event-related potentials were time-locked to the presentation of the target word to study the neurophysiological correlates of lexical and morphological learning. Waveforms of the four conditions (Stem
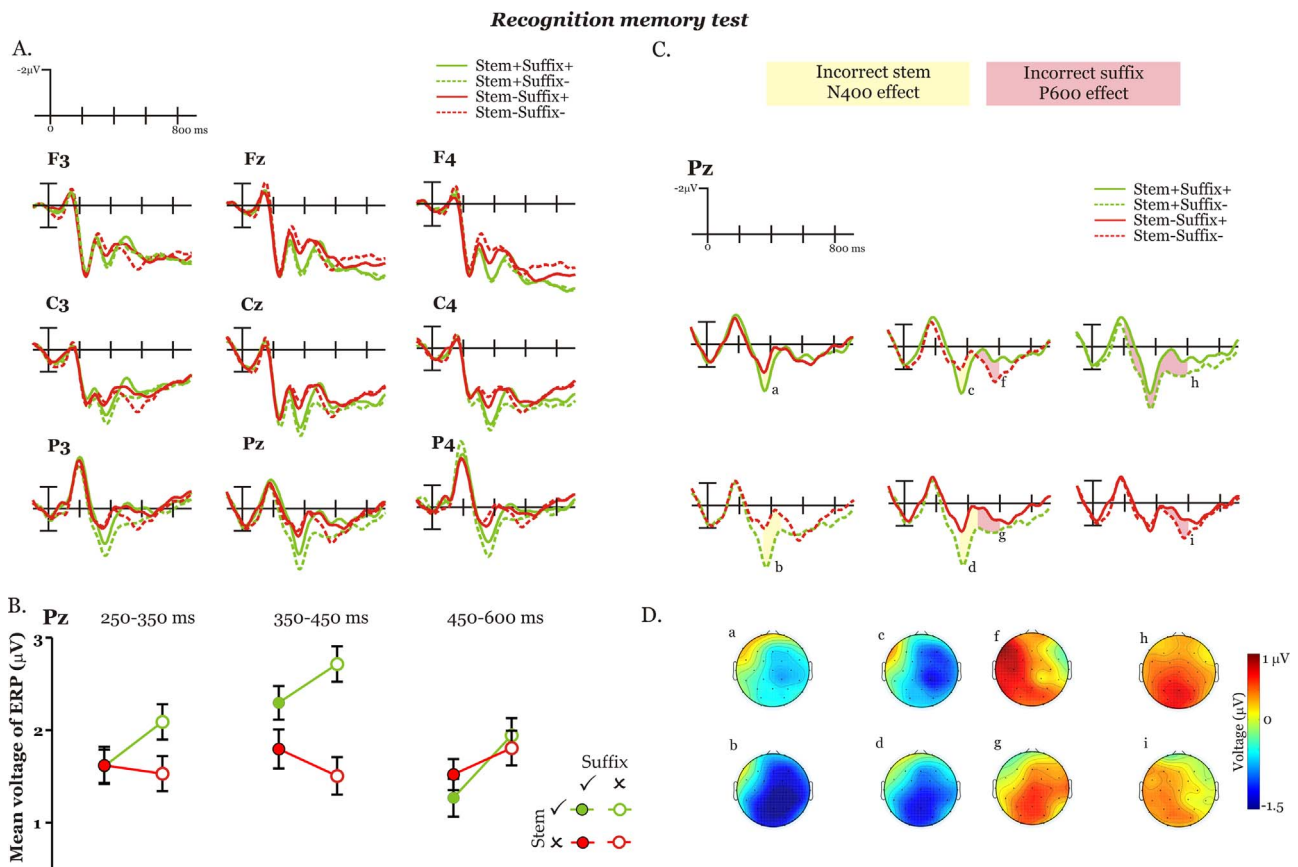
Recognition memory test

Fig. 3. [A] Average waveforms of the four conditions of the recognition memory task: red lines depict incorrect, green correct stem conditions, continuous lines correct, discontinuous lines incorrect suffix conditions. [B] The mean voltages of the four experimental conditions in the 250–350 ms (N200), 350–450 ms (N400) and 450–600 ms (P600) time windows at the Pz electrode site. [C] Mean waveforms of combinations of the conditions of the recognition memory task in the Pz electrode location to illustrate the N400 and P600 effect; topographic maps of the mean voltage difference of the N400 and P600 peaks are also depicted.
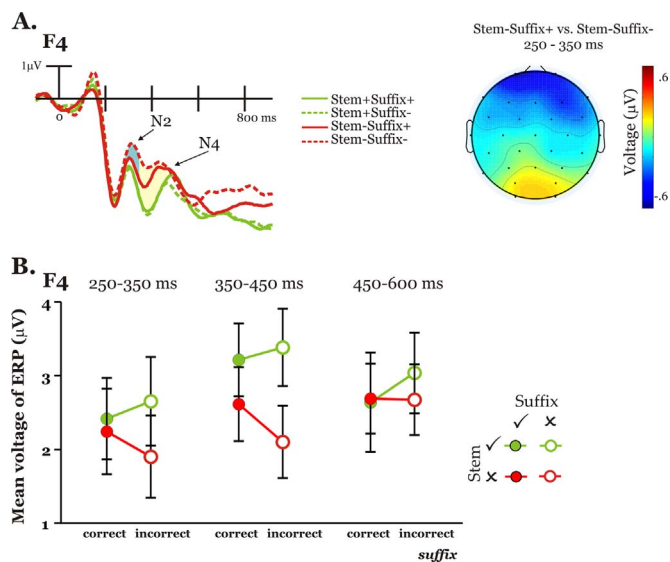
Fig. 4. [A] Average waveforms of the four conditions of the recognition memory task at the F4 location (where the N200 effect is maximal) and the scalp topography of the voltage differences between the Stem-Suffix + and Stem-Suffix- in the P200 time window: red lines depict incorrect, green correct stem conditions, continuous lines correct, discontinuous lines incorrect suffix conditions. [B] The mean voltages of the four experimental conditions in the 250–350 ms (N200), 350–450 ms (N400) and 450–600 ms (P600) time windows at the F4 electrode site.

+ Suffix +, Stem + Suffix-, Stem-Suffix + and Stem-Suffix-) are depicted at Fig. 3A. At a first glance, there seems to be a clear dissociation between stem and suffix processing. To evaluate these effects, we carried out a repeated measures ANOVA using 9 electrodes (F3/4, C3/4, P3/4, Fz, Cz, Pz) with the following factors: stem (2 levels - correct, incorrect), suffix (2 levels - correct, incorrect), laterality (3 levels - left, central, right) and anterior-posterior (3 levels - anterior, central, posterior). We performed the analysis in three time-windows: 250–350 ms, 350–450 ms and 450–600 ms (results of this analysis are presented in Table 2As the stem and suffix effects were more pronounced on the parietal electrodes, the mean voltages measured on the Pz electrode of each condition in each time window are represented in Fig. 3B.

In the earliest time window, we did not find a main effect of either stem or suffix violations. However, we found two statistically significant two-way interactions, namely Stem × Laterality, Suffix × Anterior-posterior, and a marginally significant three-way Stem x × Anterior-posterior x Laterality interaction (see Table 1). We also found a marginally significant two-way interaction: Stem × Suffix, $F(1, 15)$ = 5.94 p = .038. Visual inspection suggested that there was a fronto-central negativity peaking around 300 ms with the largest amplitude for the Stem-Suffix- condition, resembling N2-N3 conflict-related ERP components. To further investigate this effect, we conducted a one-way ANOVA with the Stem-Suffix + and Stem-Suffix- conditions on the F4 electrode site in the 300–350 ms time window. We found a significant main effect, $F(1, 15)$ = 5.59, p = .032, indicating an N2-like early negativity effect that was larger for the condition where neither the stem nor the suffix matches with the picture. Fig. 4 depicts the ERP waveforms of the four experimental conditions and the topographical map of the voltage difference between the relevant conditions in the 250–350 ms time window. This finding is consistent with previous studies of fronto-central early negativity in visual tasks (right hemisphere preponderance) when there is a mismatch between a stimulus and a mental template or when an exogenous conflict is elicited (Folstein and Van Petten, 2008; Krämer et al., 2007).

At the 350–450 ms time window, the stem by suffix by laterality by anterior-posterior analysis showed a significant main effect of stem, $F(1, 15)$ = 7.77, p = .014, but no main effect of suffix, $F(1, 15)$ = .33,

p = .58. In this time window, the incorrect stems showed an increased negativity compared to the words that contained a correct stem. We also found an interaction between stem and the anterior-posterior factor, as well as a three-way interaction between the stem and the two location factors ($p < .01$), showing that the differences between correct and incorrect stem are not evenly distributed across the scalp. Fig. 3C shows that the differences are more pronounced on the more parietal electrode sites and over the right hemisphere, convergent with the expected topography of a N400 semantic violation effect.

Analysis in the 450–600 ms time-window showed a significant main effect of suffix, $F(1, 15)$ = 12.03, p = .003, but no clear effects for stem, $F(1, 15)$ = .05, p = .83. As Fig. 3B shows, words with incorrect suffix yielded a larger positivity compared to the words that end with the correct suffix. The significant interaction between stem and the anterior-posterior factor, and a three-way interaction between the stem and the laterality and anterior-posterior factors ($p < .01$) speak for an uneven distribution of both factors across the scalp.

The analysis above confirms that the incorrect stem yielded an N400-like negativity between 350 and 450 ms independently of the correctness of the suffix, and that the incorrect suffix generated a P600-like late positivity between 450 and 600 ms regardless of the correctness of the word stem. This double dissociation between the N400 and P600 components and the two factors suggests independent linear processes for the encoding of the stem and the suffix. In addition to the expected N400 and P600 violation effects associated to lexical-semantic and morphological processing, we encountered an increase in the N2 conflict-related fronto-central negativity with larger amplitude for the double violation condition (Stem-Suffix-).

We also found a correlation between the interview scores and the difference mean amplitude of the stem + suffix + minus stem + suffix- conditions in the late (P600) time window, R = .575, p = .020, which shows that the P600 positivity is a good indicator of the acquisition of novel morphological rules.

In sum, these results also show that a very short experience with a new language is enough to induce electrophysiological changes in the cortex that give rise to a pattern that resembles some aspects of morphological and semantic processes in L1. There are some discrepancies, however, between the ERP signatures of the newly learned words and the corresponding effects typical in L1 processing. The larger frontal N2 component in the double mismatch condition namely suggests that cognitive control mechanisms of conflict-detection are activated during the task when recently learned L2 words are processed.

3.2.2. Rule generalization task

Event-related potentials were time-locked to the presentation of the target word, as in the previous task. The waveforms of 9 electrodes (F3/4, C3/4, P3/4, Fz, Cz, Pz) are presented in Fig. 5. The initial visual inspections showed two positive peaks of higher amplitude peaking around 350–800 ms for the condition where new stems carry incorrect suffixes (suffixes that violate the gender rule established by the trained WPPs) as compared to the condition where the new stems have correct gender markers. This difference was confirmed by the statistical analysis. We applied a repeated measures ANOVA using the 9 aforementioned electrodes with the following factors: suffix (2 levels - correct, incorrect), laterality (3 levels - left, central, right) and anterior-posterior (3 levels - anterior, central, posterior) in the 250–400 ms and 750–900 ms time windows. In the earlier time window, the results showed a main effect of suffix, $F(1, 15)$ = 11.09, p = .005, and no interactions between the factor suffix and electrode location. A similar positivity was present between 750 and 900 ms, $F(1, 15)$ = 7.87, p = .013.

We also found correlation between the mean amplitude of the difference waveform (correct-incorrect) of the rule generalization task in the 330–350 ms time window and the d-prime values of the same task (R = .631, p = .012) (see Fig. 6).
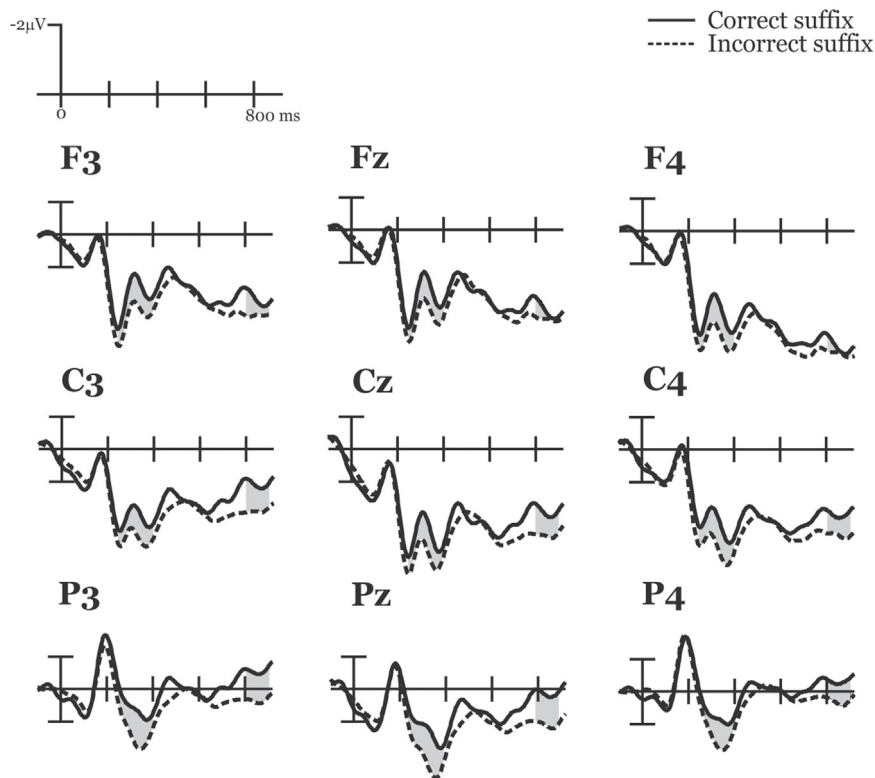
Rule generalization test

Fig. 5. Average waveforms of the rule generalization task: continuous lines represent the correct and discontinuous lines the incorrect suffix conditions.
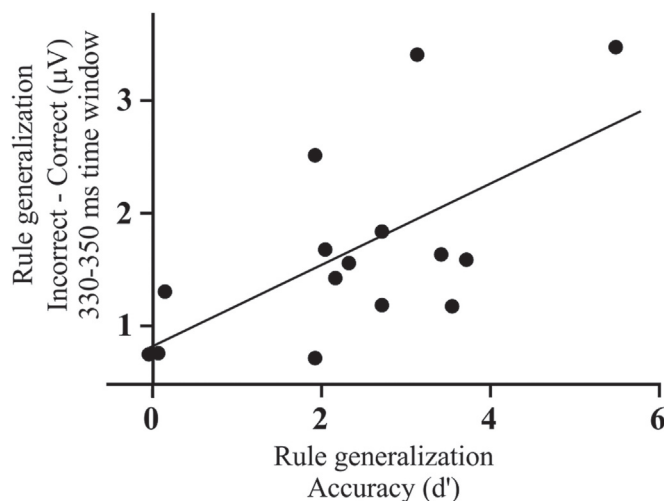

Fig. 6. Scatterplot of the mean amplitude of the difference waveform (correct-incorrect) of the rule generation task in the 330–350 ms time window and the d-prime values of the same task to illustrate the correlation between the two variables ($R = .631$, $p = .012$).

4. Discussion

In the present study, we set out to examine the neurophysiological signatures of the initial stages of lexical and morphological learning in a novel language. To that end, we used a word-picture pair learning paradigm that has provided previous behavioural evidences of both lexical and morphological learning after a limited exposure (Havas et al., 2015). Besides acquiring the novel words, in the aforementioned study the Finnish- and Spanish-speaking participant groups were able to

learn an embedded natural gender rule after about one hour of exposure to the artificial language, albeit they were not informed about the existence of such a rule. Here we used the same paradigm to seek neurophysiological signatures of early lexical-semantic and morphological learning.

4.1. Evidence for semantic and morphological processes in the early moments of L2 word learning

We found evidence for both lexical-semantic learning (learning word-picture pairs) and morphological learning (acquisition of the gender rule) in the behavioural as well as in the electrophysiological data. Our results clearly show that the participants were segmenting the to-be-learned words into the stem and suffix. Even though the average accuracy in the Stem + Suffix- condition of the recognition memory task was at chance level, the ERP results showed a robust P600 effect when the participants encountered a word containing a suffix that did not match the gender of the depicted animal, that is, when they faced a gender rule violation. Furthermore, we found an N400 effect when the stem of the word did not match the pictured animal species. In words that carried both a stem and a gender violation, we observed a biphasic N400/P600 modulation indicating that both semantic and morphological processing took place. This N400/P600 dissociation shows that target words were not processed as indivisible lexical items but were, in fact, segmented into morphemes; the meaning and function of each morpheme was contrasted against the context provided by the picture.

Moreover, in the rule generalization task where the participants were fairly accurate, we also encountered both an early and a late positivity when the completely new word carried a suffix that did not match the gender of the depicted animal. This generalization effect attests to the acquisition of the morphological gender rule by the participants. The early positivity in the range of 250–400 ms suggests

that when the stem in question is void of meaning and the only relevant information for the task is contained by the suffix, morphological analysis can start earlier probably due to a shift in attentional focus towards the suffix. This early positivity associated to rule violation is similar to the one observed by McLaughlin et al. (2010) for vowel-harmony violation with native speakers of Finnish. In that study, Finnish-like non-words that respected vowel harmony elicited greater N400 peak amplitude compared to real Finnish words. However, Finnish-like non-words that violated the vowel harmony rule elicited an early (150–300 ms) and late (around 600 ms) positivity, similar to a P600 component observed with morphosyntactic rule violation in language processing, speaking for an early rule violation effect in absence of semantic information.

However, there is another possible interpretation of the early positivity elicited by gender violation in our study. Mueller et al. (2009) found anterior-central positivity for morphosyntactic rule violations after a training session. In their study, participants were exposed to L2 language streams that contained non-adjacent dependencies but that had no semantic content. While morphosyntactic violations in the test phase elicited the modulation of the P600 component in the native language control group, the same morphosyntactic violation elicited an anterior-central positivity in the L2 group, which the authors interpreted as a variant of a P300 component. This component, specifically the P3a, is thought to be related to attentional processes and is taken as an indicator of a cognitive orienting response towards a novel stimulus. Concerning our results, the early positivity may be a variation of this P3a component, as the correctness of the suffix was relevant to the task. Therefore, it is possible that an orienting response took place. Based on their results, Mueller et al. (2009) argued that learners only acquired a set of phonological expectations about specific stimulus forms, but did not learn an abstract representation of syntactic rules concerning the dependency between the two elements. Our results, however, clearly indicate that for words trained with a meaning, morphological processing took place as indicated by the P600 modulation. This suggests that semantic processing of the newly learned words containing the morphosyntactic rules is vital to achieve L1-like language processes in a second language.

4.2. Non-language related ERP components in early morphological learning

Even though we found two language related ERP components – an N400 effect for stem violation typically indicating semantic processing (Kutas and Federmeier, 2011; Mestres-Missé et al., 2007) and a P600 effect for suffix violation normally found in morphosyntactic violation paradigms (Hagoort, 2003; Hagoort and Brown, 1999; Havas et al., 2012; Wicha et al., 2004) – we also encountered a modulation of the N2-N3 component. This is a non-language-related fronto-central early negativity that has been previously associated to the processing of conflict-related information. For example, in a selective attention flanker task where the N2 emerges around 250 ms after the presentation of the visual array, it exhibits a frontocentral scalp distribution and larger negativity on incongruent than congruent trials (Nieuwenhuis et al., 2004). Furthermore, it is assumed that this family of N2-N3 conflict-related negative components reflects the detection of a mismatch between the stimulus features presented, or between the stimulus and some previously formed internal template (Folstein and Van Petten, 2008). The N2 conflict-related component appears when active attentional processing is requested and usually when the participant is conducting some sort of a comparison process. Interestingly, N200 frontal effects have been also observed when visually presented stimulus arrays do not match participant's expectancies created by a previous cue. Similarly, the frontal N2 component was also observed in different versions of the Sternberg paradigm. Participants saw a small number of items followed by a probe item that could either match one of the previous items or not. A larger frontal N2 effect

peaking around 270–340 ms was elicited by probe items that did not match the previous item set (Ford et al., 1979; Pelosi et al., 1995). In our experiment, we observed a more pronounced frontal N2 component peaking around 300 ms in the Stem-Suffix- condition, i.e., when there was a double discrepancy between the picture and the word. The common denominator in these cases is a mismatch between a stimulus and a mental template. In our study, this template is the mental representation of the stem and the suffix and the semantic information attached to both. This finding suggests that, although language-related neural networks are engaged in the processing of the newly learned words, the task requires non-language related resources as well, such as cognitive control relying on prefrontal function. This finding converges with previous studies regarding the involvement of cognitive control processes in the early stages of language learning (for review, see Rodríguez-Fornells et al., 2009).

Several earlier studies on adult L2 morphosyntactic acquisition have shown electrophysiological evidence for learning not until after several weeks even months of L2 training (e.g., Foucart and Frenck-Mestre, 2012; McLaughlin et al., 2010). Our findings challenge these conclusions: here morphological gender violation yielded late, parieto-central positivity (P600) indicative of morphological processing after just one hour of training. This finding is also at odds with the view that the acquisition of semantic-lexical knowledge must precede morphological learning. Instead, the present results show that the two learning processes can occur more or less simultaneously However, we ought to point out that we employed a simple word-picture paradigm with a single semantically based morphological rule that does not capture the complexities of real-life L2 morphosyntactic learning. The morphological structure of the artificial language was fairly simple and the rule that the participants were to learn was related to the very salient gender feature illustrated by the cartoon-like animal characters. Despite of the implicit nature of the morphological learning task, this could have drawn the participants' attention to the morphological rule and help them to acquire it. Nonetheless, our study shows that at least under certain experimental circumstances, acquisition of the structure of totally novel multimorphemic words can take place rapidly. This phenomenon could be exploited in second language acquisition.

In summary, our results show that, at least under experimental conditions where only a single embedded morphological rule is present, adult L2 learners can extract the morphological rule quickly. Furthermore, this study suggests that lexical-semantic learning and rule-extraction can take place more or less in parallel in adult L2 acquisition. A significant contributing factor here could be that the to-be-learned morpheme had a salient, well-defined and semantically relevant meaning. This is not the case with grammatical gender or other, more abstract, morphological rules and morphosyntactic agreement processes.

Acknowledgements

References

Borovsky, A., Kutas, M., Elman, J.L., 2010. Learning to use words: event-related potentials index single-shot contextual word learning. Cognition 116 (2), 289–296. http://dx.doi.org/10.1016/j.cognition.2010.05.004.

Davis, M.H., Gaskell, M.G., 2009. A complementary systems account of word learning: neural and behavioural evidence. Philos. Trans. R. Soc. Lond. Ser. B, Biol. Sci. 364 (1536), 3773–3800. http://dx.doi.org/10.1098/rstb.2009.0111.

de Diego Balaguer, R., Toro, J.M., Rodríguez-Fornells, A., Bachoud-Lévi, A.-C., 2007.

Different neurophysiological mechanisms underlying word and rule extraction from speech. PloS One 2 (11), e1175. http://dx.doi.org/10.1371/journal.pone.0001175.

Dobel, C., Junghöfer, M., Breitenstein, C., Klauke, B., Knecht, S., Pantev, C., Zwitserlood, P., 2009. New names for known things: on the association of novel word forms with existing semantic information. J. Cogn. Neurosci. 22 (6), 1251–1261.

Dowens, M.G., Guo, T., Guo, J., Barber, H., Carreiras, M., 2011. Gender and number processing in Chinese learners of Spanish – evidence from event related potentials. Neuropsychologia 49 (7), 1651–1659. http://dx.doi.org/10.1016/j.neuropsychologia.2011.02.034.

Dumay, N., Gaskell, M.G., 2007. Sleep-associated changes in the mental representation of spoken words. Assoc. Psychol. Sci. 18 (1), 35–39.

Ferman, S., Olshtain, E., Schechtman, E., Karni, A., 2009. The acquisition of a linguistic skill by adults: procedural and declarative memory interact in the learning of an artificial morphological rule. J. Neurolinguist. 22 (4), 384–412. http://dx.doi.org/10.1016/j.jneuroling.2008.12.002.

Folstein, J.R., Van Petten, C., 2008. Influence of cognitive control and mismatch on the N2 component of the ERP: a review. Psychophysiology 45 (1), 152–170. http://dx.doi.org/10.1111/j.1469-8986.2007.00602.x.

Ford, J.M., Roth, W.T., Mohs, R.C., Hopkins, W.F., Kopell, B.S., 1979. Event-related potentials recorded from young and old adults during a memory retrieval task. Electroencephalogr. Clin. Neurophysiol. 27, 450–459.

Foucart, A., Frenck-Mestre, C., 2012. Can late L2 learners acquire new grammatical features? Evidence from ERPs and eye-tracking. J. Mem. Lang. 66 (1), 226–248. http://dx.doi.org/10.1016/j.jml.2011.07.007.

Frenzel, S., Schlesewsky, M., Bornkessel-Schlesewsky, I., 2010. Conflicts in language processing: a new perspective on the N400-P600 distinction. Neuropsychologia 49 (3), 574–579. http://dx.doi.org/10.1016/j.neuropsychologia.2010.12.003.

Frishkoff, G. a., Perfetti, C. a., Collins-Thompson, K., 2010. Lexical quality in the brain: ERP evidence for robust word learning from context. *Dev. Neuropsychology* 35 (4), 376–403. http://dx.doi.org/10.1080/87565641.2010.480915.

Gillon Dowens, M., Guo, T., Guo, J., Barber, H., Carreiras, M., 2011. Gender and number processing in Chinese learners of Spanish - Evidence from Event Related Potentials. Neuropsychologia 49 (7), 1651–1659. http://dx.doi.org/10.1016/j.neuropsychologia.2011.02.034.

Hagoort, P., 2003. Interplay between syntax and semantics during sentence comprehension: erp effects of combining syntactic and semantic violations. J. Cogn. Neurosci. 15 (6), 883–899. http://dx.doi.org/10.1162/089892903322370807.

Hagoort, P., Brown, C.M., 1999. Gender electrified: ERP evidence on the syntactic nature of gender processing. J. Psycholinguist. Res. 28 (6), 715–728. (Retrieved from). ⟨http://www.ncbi.nlm.nih.gov/pubmed/10510866⟩.

Hahne, A., Friederici, A.D., 2001. Processing a second language: late learners' comprehension mechanisms as revealed by event-related brain potentials. Biling.: Lang. Cogn. 4 (2), 123–141. http://dx.doi.org/10.1017/S1366728901000232.

Hahne, A., Mueller, J.L., Clahsen, H., 2006. Morphological processing in a second language: behavioral and event-related brain potential evidence for storage and decomposition. J. Cogn. Neurosci. 18 (1), 121–134. http://dx.doi.org/10.1162/089892906775250067.

Havas, V., Rodríguez-Fornells, A., Clahsen, H., 2012. Brain potentials for derivational morphology: an ERP study of deadjectival nominalizations in Spanish. Brain Lang. 120 (3), 332–344. (Retrieved from). ⟨http://www.sciencedirect.com/science/article/pii/S0093934×11001829⟩.

Havas, V., Waris, O., Vaquero, L., Rodríguez-fornells, A., Laine, M., 2015. Morphological learning in a novel language: a cross-language comparison. Q. J. Exp. Psychol. 68 (7), 1426–1441. http://dx.doi.org/10.1080/17470218.2014.983531.

Hopp, H., 2010. Ultimate attainment in L2 inflection: performance similarities between non-native and native speakers. Lingua 120 (4), 901–931. http://dx.doi.org/10.1016/j.lingua.2009.06.004.

Krämer, U.M., Cunillera, T., Càmara, E., Marco-Pallarés, J., Cucurell, D., Nager, W., Münte, T.F., 2007. The impact of catechol-O-methyltransferase and dopamine D4 receptor genotypes on neurophysiological markers of performance monitoring. J. Neurosci. 27 (51), 14190–14198. http://dx.doi.org/10.1523/JNEUROSCI.4229-07.2007.

Kutas, M., Federmeier, K.D., 2011. Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). Annu. Rev. Psychol. 62, 621–647. http://dx.doi.org/10.1146/annurev.psych.093008.131123.

Laine, M., Vainio, S., Hyönä, J., 1999. Lexical access routes to nouns in a morphologically rich language. J. Mem. Lang. 40 (1), 109–135.

Lehtonen, M., Harrer, G., Wande, E., Laine, M., 2014. Testing the stem dominance hypothesis: meaning analysis of inflected words and prepositional phrases. PloS One 9 (3), e93136. http://dx.doi.org/10.1371/journal.pone.0093136.

López-Barroso, D., Catani, M., Ripollés, P., Dell'acqua, F., Rodríguez-Fornells, A., Diego, DeBalaguer, R., 2013. Word learning is mediated by the left arcuate fasciculus. Proc. Natl. Acad. Sci. USA 110 (32), 13168–13173. http://dx.doi.org/10.1073/pnas.1301696110.

McLaughlin, J., Osterhout, L., Kim, A., 2004. Neural correlates of second-language word learning: minimal instruction produces rapid change. Nat. Neurosci. 7 (7), 703–704. http://dx.doi.org/10.1038/nn1264.

Mclaughlin, J., Tanner, D., Pitkänen, I., Frenck-Mestre, C., Inoue, K., Valentine, G., Osterhout, L., 2010. Brain Potentials Reveal Discrete Stages of L2 Grammatical Learning. Lang. Learn. 60 (s2), 123–150.

Mehravari, A.S., Tanner, D., Wampler, E.K., Valentine, G.D., Osterhout, L., 2015. Effects of grammaticality and morphological complexity on the P600 event-related potential component. PlosOne 1–16. http://dx.doi.org/10.1371/journal.pone.0140850.

Merkx, M., Rastle, K., Davis, M.H., 2011. The acquisition of morphological knowledge investigated through artificial language learning. Q. J. Exp. Psychol. 64 (6), 1200–1220. http://dx.doi.org/10.1080/17470218.2010.538211.

Mestres-Missé, A., Rodríguez-Fornells, A., Münte, T.F., 2007. Watching the brain during meaning acquisition. Cereb. Cortex 17 (8), 1858–1866. http://dx.doi.org/10.1093/cercor/bhl094.

Morris, J., Holcomb, P.J., 2005. Event-related potentials to violations of inflectional verb morphology in English. Cogn. Brain Res. 25 (3), 963–981. http://dx.doi.org/10.1016/j.cogbrainres.2005.09.021.

Mueller, J.L., Oberecker, R., Friederici, A.D., 2009. Syntactic learning by mere exposure. An ERP study in adult learners. BMC Neurosci. 10, 89. http://dx.doi.org/10.1186/1471-2202-10-89.

Münte, T.F., Say, T., Clahsen, H., Schiltz, K., Kutas, M., 1999. Decomposition of morphologically complex words in English: evidence from event-related brain potentials. Cogn. Brain Res. 7 (3), 241–253. http://dx.doi.org/10.1016/S0926-6410(98)00028-7.

Nieuwenhuis, S., Yeung, N., Cohen, J.D., 2004. Stimulus modality, perceptual overlap, and the go/no-go N2. Psychophysiology 41 (1), 157–160.

Pelosi, L., Hayward, M., Blumhardt, L.D., 1995. Is "memory-scanning" time in the Sternberg paradigm reflected in the latency of event-related potentials? Electroencephalogr. Clin. Neurophysiol. 96, 44–55.

Proverbio, A.M., Riva, F., 2009. RP and N400 ERP components reflect semantic violations in visual processing of human actions. Neurosci. Lett. 459 (3), 142–146. http://dx.doi.org/10.1016/j.neulet.2009.05.012.

Rodríguez-Fornells, A., Clahsen, H., Lleó, C., Zaake, W., Münte, T.F., 2001. Event-related brain responses to morphological violations in Catalan. Cogn. Brain Res. 11 (1), 47–58. http://dx.doi.org/10.1016/S0926-6410(00)00063-X.

Rodríguez-Fornells, A., Cunillera, T., Mestres-Missé, A., de Diego Balaguer, R., 2009. Neurophysiological mechanisms involved in language learning in adults. Philos. Trans. R. Soc. Lond. Ser. B, Biol. Sci. 364 (1536), 3711–3735. http://dx.doi.org/10.1098/rstb.2009.0130.

Soveri, A., Lehtonen, M., Laine, M., 2007. Word frequency and morphological processing in Finnish revisited. Ment. Lex. 2 (3), 359–385.

Tamminen, J., Davis, M.H., Rastle, K., 2015. From specific examples to general knowledge in language learning. Cogn. Psychol. 79, 1–39. http://dx.doi.org/10.1016/j.cogpsych.2015.03.003.

Tamminen, J., Gaskell, M.G., 2013. Novel word integration in the mental lexicon: evidence from unmasked and masked semantic priming. Q. J. Exp. Psychol. 66 (5), 1001–1025. http://dx.doi.org/10.1080/17470218.2012.724694.

Tamminen, J., Payne, J.D., Stickgold, R., Wamsley, E.J., Gaskell, M.G., 2010. Sleep spindle activity is associated with the integration of new memories and existing knowledge. J. Neurosci. 30 (43), 14356–14360. http://dx.doi.org/10.1523/JNEUROSCI.3028-10.2010.

Ullman, M.T., 2001. The declarative/procedural model of lexicon and grammar. J. Psycholinguist. Res. 30 (1), 37–69. http://dx.doi.org/10.1023/A:1005204207369.

Weber-Fox, C.M., Neville, H.J., 1996. Maturation contraints on functional specializations for language processing: erp and behavioral evidence in bilingual speakers. J. Cogn. Neurosci. 8 (3), 231–256.

Wicha, N.Y.Y., Moreno, E.M., Kutas, M., 2004. Anticipating words and their gender: an event-related brain potential study of semantic integration, gender expectancy, and gender agreement in Spanish sentence reading. J. Cogn. Neurosci. 16 (7), 1272–1288. http://dx.doi.org/10.1162/0898929041920487.

Zobl, H., 1998. Representational changes: from listed representations to independent representations of verbal affixes. In: Beck, M.-L. (Ed.), Morphology and its Interfaces in Second Language Knowledge. John Benjamins Publishing Company, Amsterdam, pp. 339–371.