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Different ERP profiles for learning rules over consonants and vowels

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Abstract

The Consonant-Vowel hypothesis suggests that consonants and vowels tend to be used differently during language processing. In this study we explored whether these functional differences trigger different neural responses in a rule learning task. We recorded ERPs while nonsense words were presented in an Oddball paradigm. An ABB rule was implemented either over the consonants (Consonant condition) or over the vowels (Vowel condition) composing standard words. Deviant stimuli were composed by novel phonemes. Deviants could either implement the same ABB rule as standards (Phoneme deviants) or implement a different ABA rule (Rule deviants). We observed shared early components (P1 and MMN) for both types of deviants across both conditions. We also observed differences across conditions around 400 milliseconds. In the Consonant condition, Phoneme deviants triggered a posterior negativity. In the Vowel condition, Rule deviants triggered an anterior negativity. Such responses demonstrate different neural responses after the violation of abstract rules over distinct phonetic categories.

Keywords

Consonants; vowels; rule learning; N400; MMN; functional differences

1 Introduction

Extensive research suggests that consonants and vowels are represented separately in the brain, and their processing triggers different neural responses. In one of the first systematic studies providing support for this idea, Boatman, Hall, Goldstein, Lesser and Gordon (1997) showed that direct cortical stimulation (via an implanted subdural electrode array) produced a selective impairment in the perception of consonants and not of vowels in five patients. Caramazza, Chialant, Capasso and Miceli (2000) reported the case of two patients with conduction aphasia who presented a double dissociation regarding the production of consonants and vowels. One of the patients evidenced problems in the reproduction of the vocalic segments of words, while the other patient produced errors in the consonant segments. These selective impairments, associated with different damages in the brain, suggested that consonants and vowels might have different neural representations that are

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independent of acoustic features such as sonority (see also Monaghan & Shillcock, 2003; Knobel & Caramazza, 2007). Functional magnetic resonance studies provided further evidence for this distinction at the neural level. Carreiras and Price (2008) reported distinct brain activation patterns when consonants or vowels were processed under two tasks. The authors observed different neural responses when participants had to read aloud words, and when they had to make a lexical decision over visually presented words using either consonant or vocalic information. The authors concluded that there are different neural responses when a given task is performed over consonants and over vowels. Similar conclusions were reached from analyses of Event Related Potentials (ERPs). Different electrophysiological responses were observed after consonant and vowel transpositions in pseudowords (Carreiras, Vergara & Perea, 2007), and during a lexical decision task (Carreiras, Gillon-Dowens, Vergara & Perea, 2008).

These differences in how the brain processes consonants and vowels seem to emerge early in life. Benavides-Varela, Hochmann, Macagno, Nespor and Mehler (2012) studied this issue using near-infrared spectroscopy. They familiarized Italian newborns with a CVCV nonsense word (e.g. /mimi/) and then presented them with test items that changed either the consonants (e.g. /sisi/) or the vowels (e.g. /momo/) of the familiarized word. Different blood flow patterns were observed after the presentation of consonant and vowel changes, with the latter eliciting larger reactions in newborns. Thus, studies using very different methods to register brain activity (from fMRI to NIRS and ERPs) provide converging evidence that consonants and vowels not only might have separate neural representations, but also trigger distinct neural responses. Such differences might be at the base of the separate functional roles consonants and vowels seem to play during language processing (consonants have more weight during lexical access, while vowels carry much of prosodic information; see Nespor, Peña & Mehler, 2003). A growing number of studies with speakers of different languages, at different ages, and using different tasks provide support for such a “division of labor” (as Nespor and colleagues called it) between consonant and vowels (for recent reviews, see Nazzi, Poltrock & Von Holzen, 2016; Toro, 2016).

In the present study we want to further explore how the brain reacts differently to patterns implemented over consonants and vowels. As we have mentioned before, several studies demonstrate different neural activations during word perception and production tasks when either consonant or vocalic information is modified (e.g. Benavides-Varela et al. 2012; Carreiras et al. 2007; 2008). Here we will focus on a task that involves generalizing token-independent patterns. Toro, Nespor, Mehler and Bonatti (2008) observed that adult participants find it difficult to generalize abstract rules from nonsense words using consonants but not vowels. In follow-up experiments, it was demonstrated that the difficulties in rule extraction over consonants were not caused by a lack of acoustic saliency. Even when the consonant saliency was increased over that of the vowels, participants still preferred vowels to extract rules (Toro, Shukla, Nespor and Endress, 2008). In the present experiment we will explore how the brain responses observed after the violation of an abstract rule might change depending on whether this rule is implemented over consonants or vowels. It has been demonstrated that consonants and vowels trigger different electrophysiological responses during lexical decision tasks. It is however an open issue whether similar differences could also be observed over a rule learning task. If functional

differences between consonants and vowels have their roots on early processing stages, we should be able to observe differential electrophysiological responses depending on the target phonetic category. The temporal resolution of ERPs will help us to track the time course of possible differences across consonants and vowels during the extraction of abstract structures.

2 Materials and methods

2.1 Participants

Participants were forty undergraduate students from the Universitat Pompeu Fabra (mean age= 22.34, SD=1.82). All the participants were right-handed bilingual Catalan-Spanish speakers. Participants were balanced bilinguals, as they were exposed to both languages from an early age. They signed a written informed consent form and did not report any auditory anomaly. The volunteers were paid for their participation in the study. Half of the participants ($N=20$) were assigned to the Vowel Condition, while the other half were assigned to the Consonant Condition. One participant of the Consonant condition was excluded of the experiment because he was not able to finish due to technical problems; another participant from the Consonant condition was excluded of the ERP analysis due to excessive noise.

2.2 Stimuli

A female speaker was recorded producing the target syllables *ke, ku, fa, fi, fe, fu, la, lo, li, lu, ma, mo, mi, mu, ra, ro, ri*. All the syllables were produced with a neutral intonation following the stressed syllable *pa*. The target syllables were extracted and normalized to equate for duration and intensity. Each target syllable had 330 ms of duration and each phoneme had its fundamental frequency set to 240Hz. The target syllables were combined in trisyllabic CVCVCV non-sense words.

For the vowel condition, 16 nonsense words used as standard stimuli were created by combining the phonemes */k/, /f/, /e/, /u/*. Words used as standard stimuli had an ABB rule implemented over the vowels. Learning and generalizing such patterns has been widely seen as a confirmation of abstract rule learning (see Marcus, Vijayan, Bandi Rao & Vishton, 1999). Implementing such rule over the vowels in the present experiment involved that the second vowel was repeated while the first one was different. Consonants were ordered randomly, resulting in words such as: *fufefe, fekufu, fufeke* (see Table 1). Deviant stimuli (324 nonsense words in total) were created combining phonemes not used for standard words (*/l/, /m/, /r/, /a/, /o/, /i/*). Half of the words used as deviant stimuli were Phoneme Deviants and half were Rule Deviants. Phoneme deviants differed from standard stimuli only in their phonemes. As in standard stimuli, vowels in phoneme deviants were organized following the same ABB rule, while consonants varied randomly, creating nonsense words such as *lolili, rirolo, lamomo* (see Table 1). Rule deviants differed from standard stimuli in both their phonemes and the rule used to organize the vowels. Vowels in the rule deviant stimuli were combined using an ABA rule, so the first and third vowels were the same, while the vowel in the middle was different. Consonants varied randomly, thus creating words such as *lolilo, riroli, lamoma* (see Table 1). For the behavioral test, 16 test stimuli were created

with the phonemes /f/, /l/, /m/, /a/, /u/, /i/. In half of the test stimuli the vowels followed the standard ABB rule (example: *falumu*, *fumili*, *milafa*; see Table 2). In the other half, all the vowels were different within a word, thus having an ABC structure never presented before (examples: *falumi*, *fumila*, *milafir*; see Table 2). As vowels were arranged following a repetitive structure in standard words, non-repeating vowels within a word present a good contrasting pattern for the test. None of the test words was used as standard or deviant stimuli during the experiment. The test pairs were chosen such that the only difference between the two items was in their vowels (example: *falumu* vs *falumi*).

In the Consonant condition, 16 nonsense words used as standards were composed by the phonemes /k/, /f/, /e/, /u/ (the same as in the vowel condition). In contrast to the vowel condition, the ABB rule was implemented over the consonants, so the second and third consonants were the same, while vowels varied randomly (example: *kefefe*, *fekuke*, *kefefir*; see Table 3). As in the vowel condition, two types of deviant stimuli were created using the new phonemes /l/, /m/, /r/, /a/, /o/, /i/. Half of the deviant stimuli were Phoneme Deviants that had consonants organized to the same ABB rule as standard stimuli (example: *lomomo*, *mololi*, *rolalo*; see Table 3). The other half of deviant stimuli were Rule Deviants that had consonants organized following an ABA rule (example: *lomolo*, *molomi*, *rolaro*; see Table 3). For the behavioral test, 16 test stimuli were created with phonemes /f/, /l/, /m/, /a/, /u/, /i/. Consonants in half of the test stimuli followed the standard ABB rule (example: *falilu*, *lamumi*, *mufifa*; see Table 2), while in the other half the consonants were not repeated within a word and thus followed an ABC rule never presented during the recording phase (example: *falimu*, *lamufi*, *mufila*; see Table 2). None of the test words was used as standard or deviant stimuli during the experiment. The test pairs were chosen such that the only difference between the two items was in their consonants (example: *falilu* vs *falimu*).

2.3 ERP recording

The EEG was recorded using an elastic cap of 64 channels (actiCAP) using the Modified Combinatorial Nomenclature (MNC) system. As a result, 60 electrodes were recorded from the scalp (Fp1, 2; AF3, 4, 7, 8; F1, 2, 3, 4, 7, 8; Fz, FC1, 2, 3, 4, 5, 6; FT7, 8, 9, 10; T7, 8; C1, 2, 3, 4, 5, 6; Cz; CPz; CP1, 2, 3, 4, 5, 6; TP7, 8, 9, 10; P1, 2, 3, 4, 5, 6, 7, 8; Pz; PO3, 4, 9, 10; POz; O1, 2; Oz). Two more electrodes were placed to the left and right mastoid (M1 and M2) and to control the ocular movements and blinking, two different electrodes were placed on the outer side (HEOG) and below (VEOG) the right eye. The FCz electrode was used as an online reference. The signals were sampled at a rate of 500 Hz. The electrode impedances were maintained under 10kΩ and EEG was recorded during the first phase of the experiment.

2.4 Procedure

In the present study we used an oddball paradigm. This allowed us to study the neural responses associated with change detection. This paradigm involves presenting the participants with frequent, repetitive stimuli (standard stimuli) that are sometimes replaced with a different, infrequent stimulus (deviant stimuli). The comparison of the ERPs triggered after standard and deviant stimuli provides information about the process of detecting changes in any pattern implemented over the more frequent standard stimuli. In both

conditions (Consonant and Vowel condition), participants comfortably sat in a soundproof room. They were asked to watch a silent video while nonsense words were presented through a pair of loudspeakers. The stimuli were presented in two blocks. There was a 2 minutes break between the first and second block. In each block, 808 nonsense words were presented. Of these, 608 were standard words, 100 words were Phoneme Deviants and 100 words were Rule Deviants. All the 16 standard words were randomly repeated 38 times avoiding immediate repetitions. The deviant probability was set to 0.12. Deviant stimuli were presented after a minimum of five standard stimuli.

After the presentation of the two blocks, there was a 2-alternatives forced-choice test phase. During the test phase, participants were presented with 8 pairs of novel test words. The test words presented depended on the condition (Consonant or Vowel condition). In each trial, participants were presented with a pair of test words and asked to choose which of them was more similar to the stimuli presented during the video. Order of presentation of the words was balanced. Stimulus onset asynchrony (SOA) was set to 1500 ms.

3 Results

3.1 Behavioral results

We calculated the percentage of correct responses in the 2-alternative forced choice test and compared it against chance (being chance 50%). In the vowel condition, participants' performance was above chance level ($M=61.18$, $SD=22.78$; $t(19)=2.13$, $p=.04$). In the consonant condition, participants' performance was also above chance ($M=59.86$, $SD=18.43$; $t(18)=2.33$, $p=.03$). There were no significant differences between conditions ($t(36)=-.19$, $p=.846$). Thus, participants learned the rule independently of whether it was implemented over the consonants or over the vowels in the nonsense words. This contrasts with the difficulty to learn rules over consonants observed in previous experiments (e.g. Toro, Nespor et al., 2008). However, in previous studies, participants were familiarized with the stimuli implementing the rule during 5 minutes. Under these conditions, they quickly learned the rule over the vowels, but not over the consonants. In the present experiment, they were presented with tokens instantiating the rule during approximately 30 minutes. This lengthy exposure should have given the participants enough exposure to the abstract pattern as to identify it over both consonants and vowels.

3.2 ERP results

ERP data were offline band-pass filtered from 0.1 to 30 Hz (12 dB) and re-referenced to the average of the linked mastoids. An ocular correction was applied and epochs with an amplitude $>100\mu V$ at EOG channels and with an amplitude $>100\mu V$ at EEG channels were rejected. In both conditions, epochs of 800 ms were used with a baseline from -100 to 0ms relative to the third syllable onset. The criterion we used to include a participant in the analysis was to have a minimum of 80% of valid trials. The mean percentage of trials kept per subject was of 94.06% for the vowel condition and of 93.25% for the consonant condition.

We applied a cluster mass permutation test (Maris and Oostenveld, 2007) separately on each condition (Consonant and Vowel conditions). In this analysis the mean difference between standards and deviants is calculated for every channel-data point pair. These pairs are clustered on the basis of temporal and spatial adjacency and their cluster-level statistic is calculated. Then, a random partition is repeated several times for every cluster and the cluster-level p-value is obtained. One thousand permutations were then run to assess the probability of finding clusters with higher statistics if the standard and deviant stimuli were assigned randomly. Because there are two types of deviant stimuli in the current study (Phoneme Deviants, Rule Deviants), we performed 2 comparisons, Standard vs Rule Deviants and Standard vs Phoneme Deviants. Previous studies exploring rule learning analysis (e.g. De Diego-Balaguer et al., 2007; Sun et al. 2012) used Regions of Interest (ROIs) to analyze their observed ERPs. Thus, to better explore effects at target areas that have been seen to be key in the processing of abstract regularities in artificial language learning experiments, we defined six ROIs for the analysis: Left anterior (electrodes F3, F1, FC3, FC1), Right anterior (electrodes F4, F2, FC4, FC2), Left central (electrodes C3, C1, CP3, CP1), Right central (electrodes C4, C2, CP4, CP2), Left posterior (electrodes P5, P3, P1, PO3), and Right posterior (electrodes P4, P2, P6, PO4). As we will detail in the next section, Phoneme and Rule deviants triggered in both the Consonant and the Vowel conditions an early (around 50 ms) frontal positivity quickly followed by a negativity around 150 ms. Apart from these shared early components, we also observed some relevant differences across conditions. In the Consonant condition, Phoneme deviants triggered a negativity in posterior electrodes after 400 ms. In the Vowel condition, it was the Rule Deviants that triggered a frontal negativity from 440 to 580 ms.

3.3 Consonant condition

We observed a significant positivity from 60 to 152 ms in the left anterior region after Phoneme deviant stimuli (cluster mass permutation test, $p=.035$). This response was followed by a negativity from 152 to 286 ms in the left anterior region (cluster mass permutation test, $p=.002$) and from 150 to 284 ms in the right anterior region (cluster mass permutation test, $p<.001$). More central for the present study, a negative response was also observed after 400 ms in the central and the posterior electrodes (see Figure 1). Timing of this negativity was from 454 to 518 ms in the right central region (cluster mass permutation test, $p=.023$), from 410 to 588 ms in the right posterior region (cluster mass permutation test, $p=.003$), and from 418 to 546 ms in the left posterior region (cluster mass permutation test, $p=.012$).

Rule deviant stimuli also triggered a significant positivity from 58 to 152 ms in the left anterior region (cluster mass permutation test, $p=.028$). This response was followed by a negativity from 150 to 246 ms in the right anterior region (cluster mass permutation test, $p=.05$). In posterior electrodes, we observed an early negativity. Timing of this negativity was from 50 to 158 ms in the right region (cluster mass permutation test, $p=.022$) and from 64 to 144 ms in the left region (cluster mass permutation test, $p=.039$; see Figure 1). No other significant response was observed after Rule deviant stimuli.

In the visual inspection of the Grand Average Data the early frontal negativity observed after the Phoneme deviants seems to have more amplitude than after the Rule deviants. To explore this possible difference across deviant items, we conducted a repeated measures ANOVA with the peak voltages of the difference wave (subtracting the responses of standard and deviants) for both type of deviant items. The within-subject factors were Hemisphere (2 levels; left and right), Position (4 levels; left, middle-left, middle-right and right), and Stimulus (2 levels; Rule deviant and Phoneme deviant). The electrodes included in this analysis were F3, F1, FC3, FC1, F4, F2, FC4 and FC2. The results were corrected with the Greenhouse-Geisser adjustment when the sphericity was violated. The Bonferroni correction was applied on multiple comparisons. The results showed a main effect for Stimulus ($F(1,17)=4.51$, $p=.049$) and Hemisphere ($F(1,17)=4.61$, $p=.046$). Results thus confirm that Phoneme deviants triggered a negative component with more amplitude than Rule deviants, and this negativity was larger in the left hemisphere than in the right hemisphere.

We also explored possible differences across deviant stimuli for the peak voltages of the difference waves in the time window of the early positivity triggered by both Rule and Phoneme deviants. We did not observe any main effects or interactions.

3.4 Vowel condition

Phoneme deviants triggered a significant positivity from 42 to 140 ms in the left anterior region (cluster mass permutation test, $p=.01$) and from 42 to 130 ms in the right anterior region (cluster mass permutation test, $p=.025$). This was followed by a negative response from 150 to 240 ms in the right anterior region (cluster mass permutation test, $p=.033$; see Figure 2). No other significant responses were observed after Phoneme deviants.

Rule deviants also triggered a significant positivity from 58 to 132 ms in the left anterior region (cluster mass permutation test, $p=.01$) and from 52 to 130 ms in the right anterior region (cluster mass permutation test, $p=.022$). This was followed by a negativity from 152 to 236 ms in the left anterior region (cluster mass permutation test, $p=.01$), and from 148 to 242 ms in the right anterior region (cluster mass permutation test, $p=.012$). Interestingly, a significant negativity was also observed from 440 to 584 ms in the right anterior region (cluster mass permutation test, $p=.030$) and from 362 to 484 ms in the right central region (cluster mass permutation test, $p=.038$; see Figure 2).

When we compared the responses triggered by Phoneme and Rule deviants in the time windows for both the early frontal positivity and negativity we did not observe any main effects or interactions. Both types of deviant stimuli generated very similar early electrophysiological responses in the Vowel condition.

3.5 Comparisons across conditions

As we have described above, in both the Consonant and Vowel conditions we observed an early positivity followed by a frontal negativity when both Rule and Phoneme deviants were presented. We thus explored the possible differences across conditions for these two early frontal components. We conducted a Hemisphere x Position x Stimulus ANOVA with the between-subject factor Condition (2 levels; Consonant and Vowel). We did not observe any significant differences across conditions in the positivity window (from 50 to 100 ms).

However, in the time window for the frontal negativity (from 100 to 150 ms), there was a marginally significant Stimulus x Condition interaction ($F(1,36)=3.91$, $p=.056$; see Figure 3). Pairwise comparisons showed a significant difference between Phoneme deviants and Rule deviants in the Consonant condition ($p=.035$). There was also a significant Hemisphere x Stimulus x Condition interaction ($F(1,36)=4.94$, $p=.033$). Pairwise comparisons showed a significant difference between Phoneme deviants and Rule deviants in the Consonant condition specifically in the left hemisphere ($p=.002$). Moreover, responses after the Phoneme deviants were larger in the Consonant condition than in the Vowel condition only in the left hemisphere ($p=.027$; for a similar response to local changes in acoustic sequences see Escera, Alho, Winkler and Näätänen, 1998).

4 Discussion

Several studies suggest there is a division of labor between consonants and vowels during language processing (Nespor et al., 2003). Supporting this hypothesis, there is consistent evidence demonstrating that consonants are preferentially used over vowels during lexical access (e.g. Nazzi et al., 2016). Studies using very different methodologies (including neuropsychological evaluations with patients, fMRI, NIRS and ERPs experiments) suggest that consonants and vowels have different neural representations (e.g. Boatman et al. 1997; Benavides-Varela et al. 2012; Caramazza et al. 2000; Carreiras et al. 2007; 2008). In the current study we wanted to explore the responses triggered by violations of a rule implemented over either consonants or vowels. We observed a dissociation in the neural responses. When the rule is implemented over the consonants (Consonant condition) presenting nonsense words with novel phonemes elicits a posterior negative response around 400ms. In contrast, when the rule is implemented over the vowels (Vowel condition) presenting nonsense words that did break the standards' rule, elicits a frontal negativity at about 400ms. These results are compatible with the different functional roles that have been described for different phonetic categories and, to the best of our knowledge, are the first to show distinct activations for consonants and vowels during abstract pattern learning.

4.1 Shared early components

In all the conditions (Consonant and Vowel condition) and after both Rule and Phoneme deviants we observed a frontal positivity that is congruent with a P1 component. The P1 normally occurs 50 ms after stimulus presentation and can be distributed over frontal and posterior sites. This component has been observed after changes in acoustic stimuli and has been proposed to reflect the arousal level of the participants listening the speech sequences (Key, Dove & Maquire, 2005). The P1 has also been observed after subtle variations on the quality of synthesized diphthongs (Morris, Steinmetzger & Tondering, 2016). In the current experiment, this component was observed around 50 ms after the onset of the last syllable in deviant stimuli, signaling the processing of the novel syllable transitions present within the deviant stimuli. Such processing likely involved online updating of the incongruent information present in the deviants (in the form of novel transitions between syllables) with respect to the standards.

More central to our study, we observed a frontal negativity around 150 ms both in the Vowel and the Consonant condition. Timing and distribution of this negativity is congruent with a mismatch negativity (MMN). The MMN has been observed after the presentation of deviant and novel auditory stimuli, including speech (e.g. Escera et al., 1997; Pulvermüller and Shtyrov, 2003). In the current experiment, the MMN component was observed in all the conditions after both Phoneme and Rule deviants. As we have emphasized above, all the deviant stimuli were created using novel phonemes never used for the standard words. Thus, our results are in line with those reported by Bekinschtein and collaborators (2009) showing that local, physical changes in the auditory input typically trigger a MMN (see also Bahmann, Gunter, & Friederici, 2006 for a similar conclusion). In our case, phoneme changes from standard to deviant stimuli would trigger such component. The fact that this component was consistently found in the present experiment across conditions and types of deviant stimuli suggests participants readily detected the changes from standards to deviants. Detection of such changes was reflected in a MMN when novel words were presented in the sequence of standard stimuli.

Differences in the amplitude of the MMN observed across conditions could be telling regarding differences between consonants and vowels. In the Consonant condition, the amplitude of the MMN was greater after Phoneme deviants than after Rule deviants (see Figure 3). This difference across deviant stimuli was not observed in the Vowel condition. Even more, the amplitude of the MMN for Phoneme deviants was greater in the Consonant than in the Vowel condition. Thus, changes in the phonemes defining standard stimuli triggered stronger responses when these changes were made over consonants than over vowels (see also Carreiras et al., 2007; 2008). This finding fits well with the claim that consonants tend to be given more weight during word recognition than vowels (e.g. Nazzi et al., 2016; Nespor et al., 2003) by demonstrating different neural responses across phonetic categories. Interestingly, these differences can be observed as soon as 100 ms after the presentation of a violation, suggesting differences during the early stages of processing.

4.2 Anterior and Posterior N400

In the Consonant Condition we observed a negative response around 400 ms in central and posterior regions after the presentation of Phoneme Deviants. That is, the negative component was triggered after words with new phonemes that followed the same pattern as standard stimuli. The N400 has been associated with lexical search (e.g. Kutas & Federmeier, 2000; Lau, Phillips, & Poeppel, 2008). In the field of artificial language learning, it has been shown that items following legal patterns in a language trigger more robust lexical search mechanisms than items following illegal patterns (Rossi et al., 2011). If participants are presented with pseudowords following a native phonotactic pattern and with pseudowords following a non-native phonotactic pattern, the native-like items trigger a larger N400 component when compared to the non-native-like pseudowords (Rossi et al., 2011). In fact, pseudowords with illegal phonotactic combinations are more rapidly discarded as potential lexical candidates (Rossi, Hartmüller, Vignotto & Obrig, 2013). As a result, only 'legal' pseudowords are to be lexically examined (see also Friedrich & Friederici, 2005). In our study, only those nonsense words following the standards' structure (Phoneme deviants) triggered a N400. This might indicate that participants were assessing

the lexical status of the items, and deviants that kept the same structure as frequent, standard items triggered more robust lexical search mechanisms than deviant items with a different structure (see also De Diego-Balaguer, Toro, Rodriguez-Fornells and Bachoud-Lévi, 2007 for similar results using artificial languages).

When the rule was implemented over the vowels (Vowel Condition), we observed a negative component in the frontal region around 400 ms only after Rule deviant stimuli. That is, the negativity was triggered when there was a change in the abstract rule. As we have mentioned before, the N400 component has traditionally been associated with lexical processes. However, some studies have observed the N400 in artificial language learning tasks related to abstract structure processing. The N400 has been observed after the presentation of syntactically incorrect sequences lacking semantic information (Mueller, Girgsdies & Friederici, 2008), during abstract grammar processing (Choudhary, Schlesewsky, Roehm & Bornkessel-Schlesewsky, 2009), and with non-members in a categorization task (Núñez-Peña & Honrubia-Serrano, 2005). Tabullo and collaborators (2011) compared the patterns of neural activation for infrequent, frequent, correct and incorrect pseudowords. The authors observed that only the incorrect syntactic sequences elicited a N400 component. In our study, we also observed a frontally distributed N400, which contrasts with the posterior distribution of the N400 component that has been reported in lexical decision tasks (see Rossi et al., 2011; 2013; Friedrich & Friederici, 2005). Importantly, Sun et al. (2012) also observed a similar topographical distribution for this negativity. In their study, the authors trained participants with pseudowords following an abstract rule. Once participants learned the rule, they were presented with new stimuli following the same or a different pattern. The authors observed a frontal N400 after the presentation of stimuli with different patterns. This negativity appeared only in the last block of training (not in the initial blocks) suggesting it signaled abstract rule learning. Moreover, functional magnetic resonance imaging studies exploring syntax and abstract rule processing have also shown frontal brain activations (Badre, Kayser & D'Esposito, 2010; Forkstam, Hagoort, Fernandez, Ingvar & Petersson, 2006; Opitz & Friederici, 2004; Uddén et al., 2008). Thus, the emergence of a frontally distributed negativity around 400 ms observed in our results is congruent with previous studies showing similar brain activation patterns during rule learning. The fact that this negativity was only observed in the Vowel condition when the rule defining standard stimuli was violated suggests that the participants were processing their abstract structure.

4.3 Functional distinctions between consonants and vowels

In the present study we observed that the phonological category that implemented the rule modulated the neural responses triggered after its violations. While changes in phonemes triggered a posterior N400 in the Consonant condition, only changes in rules triggered a frontal N400 in the Vowel condition. It has been claimed that changes in the N400 component might reflect changes in the processing strategy that participants are using during a given task. Rossi et al. (2013) argued that when participants had to engage in categorization training, the lexical N400 effect was partially inverted when compared to a passive listening task (see also Silva-Pereyra et al., 2003). In the present study we did not change task instructions across conditions. We changed however the source of the target regularity (either the consonants or the vowels). After 30 minutes of exposure, all the

participants had learned the rule in both conditions (as reflected by above-chance performance in the behavioral task). However, the ERP analysis suggests that different processes were triggered in each condition. Changes in consonants triggered electrophysiological responses associated with lexical processes (stronger MMN after phoneme changes, and central and posterior negativities after 400 ms) while changes in the abstract pattern implemented over vowels triggered responses associated with syntactic learning (frontal negativities after 400 ms). Thus, the results suggest that consonants were more heavily used for word recognition while vowels were used to process the abstract rule.

Participants in our experiment were bilingual Catalan-Spanish speakers. There are studies showing that adult bilingual and monolingual speakers show differences in some aspects of cognitive processing such as in their executive functions (for a recent review see Costa & Sebastián-Gallés, 2014). In fact, experiments have found that 12-month-old bilingual infants can learn two abstract rules (similar to the ones tested in the present experiment) at the same time, while their monolingual peers learn only one (Kovacs & Mehler, 2009). Results from our study suggest that participants were able to detect patterns over both consonants and vowels. It would thus be interesting to explore the extent to which some of the components we observed are linked to bilingualism. More specifically, it would be important to study if there could be an influence in the N400 component, as it is a late response related to top-down cognitive processing.

Our results add to a growing literature demonstrating that vowels and consonants trigger different neural responses, specifically showing such differences during abstract rule learning. As we described above, differences in how the brain processes consonants and vowels seem to emerge very early in life (Benavides-Varela et al., 2012). The different brain responses we observed in the present study might be grounded on specialization processes that seem to emerge during language learning. These processes would lead to a division of labor across phonetic categories that could facilitate the paramount task of finding relevant information in the linguistic signal (see Nespor et al., 2003). Thus, both at the neural and at the functional level there is converging evidence that consonants and vowels have different representations and might be used differently during language processing.

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Figure 1.

ERPs corresponding to Standards (black line), Phoneme deviants (blue line) and rule deviants (red line) for the Consonant condition. Middle frontal (Fz) and posterior (Pz) electrodes are shown. The polarity maps correspond to the N400 time window. The left map corresponds to the presentation of Phoneme deviants and the right map corresponds to the presentation of Rule deviants.

Figure 2.

ERPs corresponding to Standards (black line), Phoneme deviants (blue line) and Rule deviants (red line) for the Vowel condition. Middle frontal (Fz) and middle posterior (Pz) electrodes are shown. The polarity maps correspond to N400 time window. The left map corresponds to the presentation of Phoneme deviants and the right map corresponds to the presentation of Rule deviants.

Figure 3.

Means of the MMN amplitude (deviant minus standard) in Fz electrode for the Consonant and Vowel condition. The black bars correspond to the Phoneme deviants and the white bars correspond to the Rule deviants.

Table 1
Nonsense words used in the Vowel condition

Standards	Phoneme deviants	Rule deviants
<i>fefufu</i>	<i>lalili</i>	<i>lalila</i>
<i>fefuku</i>	<i>lalimi</i>	<i>lalima</i>
<i>fekufu</i>	<i>laliri</i>	<i>lalira</i>
<i>fekuku</i>	<i>lalolo</i>	<i>lalola</i>
<i>fufefe</i>	<i>loliri</i>	<i>loliro</i>
<i>fufeke</i>	<i>lomala</i>	<i>lomalo</i>
<i>fukefe</i>	<i>lomama</i>	<i>lomamo</i>
<i>fukeke</i>	<i>lomara</i>	<i>lomaro</i>
<i>kefufu</i>	<i>mimomo</i>	<i>mimomi</i>
<i>kefuku</i>	<i>mimoro</i>	<i>mimori</i>
<i>kekufu</i>	<i>mirala</i>	<i>mirali</i>
<i>kekuku</i>	<i>mirama</i>	<i>mirami</i>
<i>kufefe</i>	<i>rarolo</i>	<i>rarola</i>
<i>kufeke</i>	<i>raromo</i>	<i>raroma</i>
<i>kukefe</i>	<i>raroro</i>	<i>rarora</i>
<i>kukeke</i>	<i>rilala</i>	<i>rilali</i>

Note. List of the 16 nonsense words used as standards in the Vowel condition and examples of Phoneme and Rule deviants. In standards, vowels were arranged following a specific rule (ABB), while the consonants varied randomly. Phoneme deviants implemented the same rule over novel phonemes. Rule deviants implemented a different rule (ABA) over novel phonemes.

Table 2
Stimuli used in the Vowel and Consonant condition in the behavioral test

	Correct	Incorrect
Vowel condition	<i>falumu</i>	<i>falumi</i>
	<i>fulala</i>	<i>fulali</i>
	<i>fumili</i>	<i>fumila</i>
	<i>lafimi</i>	<i>lafimu</i>
	<i>lumifi</i>	<i>lumifa</i>
	<i>mafulu</i>	<i>mafuli</i>
	<i>milafa</i>	<i>milafu</i>
	<i>mimulu</i>	<i>mimula</i>
Consonant condition	<i>falilu</i>	<i>falimu</i>
	<i>fimuma</i>	<i>fimula</i>
	<i>fulali</i>	<i>fulami</i>
	<i>lafifi</i>	<i>lafimi</i>
	<i>lamumi</i>	<i>lamufi</i>
	<i>limamu</i>	<i>limafu</i>
	<i>mufifa</i>	<i>mufila</i>
	<i>mululi</i>	<i>mulufi</i>

Note. Two types of stimuli were presented in the test phase; correct test stimuli followed the same ABB rule as Standards. Incorrect test stimuli did not follow the same rule. In the Vowel condition the rules were carried by vowels and consonants varied randomly. In the Consonant condition the rules were carried by consonants and vowels varied randomly.

Table 3
Nonsense words used in the Consonant condition

Standards	Phoneme deviants	Rule deviants
<i>fekeke</i>	<i>lamama</i>	<i>lamala</i>
<i>fekeku</i>	<i>lamami</i>	<i>lamali</i>
<i>fekuke</i>	<i>lamamo</i>	<i>lamalo</i>
<i>fekuku</i>	<i>lamima</i>	<i>lamila</i>
<i>fukeke</i>	<i>lomimo</i>	<i>lomilo</i>
<i>fukeku</i>	<i>lomoma</i>	<i>lomola</i>
<i>fukuke</i>	<i>lomomi</i>	<i>lomoli</i>
<i>fukuku</i>	<i>lomomo</i>	<i>lomolo</i>
<i>kefefe</i>	<i>mirari</i>	<i>mirami</i>
<i>kefefu</i>	<i>miraro</i>	<i>miramo</i>
<i>kefufe</i>	<i>mirira</i>	<i>mirima</i>
<i>kefufu</i>	<i>miriri</i>	<i>mirimi</i>
<i>kufefe</i>	<i>ramoma</i>	<i>ramora</i>
<i>kufefu</i>	<i>ramomi</i>	<i>ramori</i>
<i>kufufe</i>	<i>ramomo</i>	<i>ramoro</i>
<i>kufufu</i>	<i>rilala</i>	<i>rilara</i>

Note. List of the 16 nonsense words used as standards in the Consonant condition and examples of Phoneme and Rule deviants. In standards, consonants were arranged following a specific rule (ABB), while the vowels varied randomly. Phoneme deviants implemented the same rule over novel phonemes. Rule deviants implemented a different rule (ABA) over novel phonemes.