# The influence of Syllabic Structure on Computational Processes: an Electrophysiological and Behavioural Approach

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A la meva *iaia*,
per la seva passió, compassió i carinyo,
per les estones que hem rigut i filosofat,
i per ser tot un exemple a seguir.
T'estimo.

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*If you thought that science was certain*
*–well, that is just an error on your part.*
*— Richard Feynman*

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# ABSTRACT

In language learning two mechanisms are of critical importance, namely, rule learning and statistical learning. Additionally, an important linguistic unit, the syllable, has been proposed to be the unit of speech segmentation and speech production. The present dissertation explores the influence of syllabic structure on rule learning and statistical learning mechanisms. First, I explored the interference of syllabic structure changes over adjacent repetition-based rules and statistical word segmentation in a series of behavioural experiments. Then, I explored the ERP signatures of a syllabic structure change over adjacent and non-adjacent repetition-based rules. Overall, results show that the learnability of abstract adjacent or non-adjacent repetition-based rules and statistical learning are not interfered by a change in syllabic structure. Our results also show that the extraction of regularities over syllables was easier to perform than over vowels, attesting the pre-eminent role of the syllable in speech processing. The electrophysiological responses to syllabic structure changes were readily detected a few hundred milliseconds after the presentation of the stimulus, manifesting the automatic perceptual nature of its detection.

# RESUM

En l’aprenentatge d’una llengua intervenen dos mecanismes bàsics, l’aprenentatge de regles i l’aprenentatge de relacions estadístiques. A més, s’ha proposat la síl·laba com a unitat amb rellevància lingüística per aquest estudi. La present dissertació explora la influència de l’estructura sil·làbica en els mecanismes d’aprenentatge de regles i de relacions estadístiques. Primerament, en una sèrie d’experiments comportamentals, exploro la interferència que el canvi d’estructura sil·làbica genera en regles repetitives adjacents i en mecanismes estadístics de segmentació de paraules. Després, exploro les respostes cognitives evocades del canvi d’estructura sil·làbica en l’aprenentatge de regles repetitives adjacents i no adjacents. Els resultats mostren que l’aprenentatge de regles repetitives adjacents i no adjacents, i l’aprenentatge de relacions estadístiques, no són interferits per un canvi d’estructura sil·làbica. L’extracció de regularitats sobre síl·labes va ser més fàcil que sobre vocals, confirmant el paper preeminent que la síl·laba té en el processament del llenguatge. La resposta electrofisiològica del canvi d’estructura sil·làbica va ser detectada amb rapidesa, tan sols uns dos-cents mil·lisegons després de la presentació de l’estímul, posant de manifest, doncs, la naturalesa automàtica d’aquesta detecció.

# PREFACE

As an infant I grew up in a trilingual environment. When I was eleven months old, my family moved to the United States and we lived there for five years. My parents would speak to me in Catalan, between them in Spanish, and outside the doors of my home people would address me in English. When I was old enough, my mom let me play with other children in the building where we lived. But as a concerned parent, she asked another neighbor parent if I was able to get along well with the other children since I did not know any English. Far from the truth, the neighbor told my mom, in a confused tone, that she didn't know what she was talking about since I spoke English perfectly (for my age). And I even learned Spanish from my parents, even though they never addressed us in that language. When we played, my brother and I would speak between us in Catalan, interspersing English and Spanish words or phrases here and there. But I knew perfectly to adapt to my surroundings' language knowledge. For instance, I never tried to address my kindergarten teacher in Catalan or Spanish. A funny fact about growing up in an environment where the only place you speak your native language is at home, is that you can easily invent a word and confuse it with an actual word from the lexicon. My brother and I –most probably my brother– invented the Catalan word enganxada for scotch tape, and for many years I thought it was correct because it made total sense. In Catalan, enganxada means being stuck or glued, in the female form. So we adopted a word from the Catalan language and used it for a material that its purpose is to glue objects together. We also made up names for our stuffed teddy bears and assign a speaking language, that could be either one of the three languages we knew, to each of them. When we came back to Barcelona, the influence of English over Catalan was so strong that, for a few months, I would use the word so in Catalan sentences, even pronouncing it following the Catalan phonology. Nowadays my American-English accent, indelible in my brain, is a testimony of that period in my life.

Because of my unique experience with language, pursuing a doctorate in language acquisition made me value and feel amazed at how infants can achieve such an extraordinary milestone as is learning a language (or a number of languages) with apparent ease. To acquire a language, we need to be able to segment the continuous speech into words and extract the underlying rules (grammar) that govern the linguistic signal. Moreover, during the acquisition of a language we use specialized constraints, that are only present in humans, and general-purpose mechanisms, that we share with other species (Toro, 2016). These constraints and mechanisms shape our perception of the raw auditory input, mimicking a filter that preprocesses a signal, to make it readily available to be efficiently processed. For instance, infants up to 6 months of age can discriminate phonetic contrasts of any language, and from 6 months, babies become tuned to only the phonetic contrasts present in their native language (Kuhl, 2004). This way, infants can efficiently focus in learning the language available in their surroundings, a quality that will help them use their limited computational power to decode their native language. Since birth, we are equipped with a mechanism that help us segment the stream into intelligible words by computing probabilities between syllables, called statistical learning (Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009). Thus, to be able to segment "Thetableispurple" into words we compute the probabilities of co-occurrence between syllables, called transitional probabilities (TPs). For instance, the probability that "ta" follows "ble" is much higher than the probability that "is" follows "pur", since "ispur" is not a possible word and its TPs are lower than "table". Neonates are also able to readily detect adjacent repetitions and use this perceptual constraint to extract rule-based regularities from a speech stream (Gervain, Macagno, Cogoi, Peña, & Mehler, 2008). We also present some limitations due to the way language shapes our brain, that transcend the automaticity of certain mechanisms. For instance, human adults are unable to extract simple adjacent repetition rules when they are computed over impossible syntactic categories (e.g. noun-noun-verb, Endress & Hauser, 2009). Moreover, there is evidence that when we process a speech signal there are brain regions that are naturally entrained to certain oscillations presented in the signal. Concretely, the frequency rates of the syllable and the phoneme. Syllabic rates correspond to the theta band, while the phonemic rates correspond to the gamma band. And it has been seen that phonemic-gamma oscillations are modulated by syllabic-theta oscillations after speech-related input, prominently in left-lateralized language-related brain regions (Morillon et al., 2010).

Thus syllables, more than phonemes, are an important unit in language processing.

In the present dissertation I wanted to explore the influence of syllabic structure in basic language learning mechanisms, such as rule learning and statistical learning. This thesis is divided into four chapters. In Chapter 1, I expose briefly the main findings on language learning mechanisms, constraints, and on the importance of the syllable during language processing. Chapter 2 and 3 are the experimental sections. In Chapter 2, a series of behavioural experiments explore if the syllabic structure can interfere with rule learning and statistical learning. In Chapter 3, electrophysiological studies are performed to explore the interference of the syllabic structure with adjacent and non-adjacent rule patterns. In Chapter 4, I present the main findings of each chapter and discuss the implications of the results to make them fit in the actual literature in language processing. Then, I explore future lines of research and, finally, I summarize the main conclusions that can be drawn from the present work.

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# Chapter 1

# General Introduction

*I have created in her a being of exquisite logic*
*to rival the best of our species.*
–Sarek in Star Trek: Discovery

Suppose that you had a baby named Donna. During the course of her life, Donna would need to learn the language that you are speaking –and we know that this successfully happens during the first years of the infant's life in a quite remarkable way. There seems to be certain mechanisms that Donna uses since birth in order to acquire a language, and these mechanisms may likely be automatic in nature due to the ease of acquiring a language that any healthy child experiences. Therefore, these mechanisms facilitate that any time a person speaks to Donna, she is able to segment the continuous stream, with no pauses, into words, link each word to a meaning or representation, and understand the underlying hierarchy of how words form phrases, and how phrases form sentences. At each level of these linguistic structures, namely syllables, words, phrases or sentences, Donna is able to group them into meaningful pieces of information. In this dissertation, we will explore the role of an important unit in speech, the syllable, in statistical learning, the mechanism that allows Donna to segment a continuous stream into words solely by means of statistical cues carried by syllables that lead to correctly parsing the stream; and rule learning, the token-independent mechanism that allows Donna to group syllables into words, words into phrases, and phrases into sentences. To better explain the issues tackled in the present dissertation I will begin by describing the two mechanisms of language acquisition that are the focus of the present work, namely statistical learning and rule learning. Then, I will discuss evidence regarding the importance of the syllable for the organization of language. Finally, I will present in more detail the goal of this dissertation and give an extended account of the content of each experimental chapter.

## 1.1 Statistical Learning

In this thesis, we understand statistical learning as the mechanism that parses a speech stream into distinct words by computing transitional probabilities or frequencies of co-occurrence between syllables, thus boosting word learning. This automatic mechanism is key to acquire a language and is known to be present since birth (Teinonen et al., 2009). Teinonen et al. (2009), suggested that neonates automatically extracted statistical regularities from a stream of nonsense words, obtaining cues to word boundaries. These boundaries were defined by the distinct neural signatures elicited by initial syllables compared to final syllables in the newborns tested in the study.

### 1.1.1 Behavioural statistical learning studies

In a seminal study, Saffran, Aslin, and Newport (1996) showed that 8-month-old infants were able to segment connected speech that only had statistical cues to word boundaries. Infants were presented with a continuous stream formed by four nonsense words randomly repeated along the stream in a way that probabilities of co-occurrence of syllables within words was 1, and probabilities of co-occurrence of syllables between words was 0.33. The authors claimed that infants were able to detect word boundaries from the stream with no pauses and no cue other than the transitional probabilities (TPs) between syllables. That is, infants distinguish between words, that had TPs of 1 between syllables, and part-words, that had a dip in TPs due to one syllable spanning word boundaries (see Figure 1).

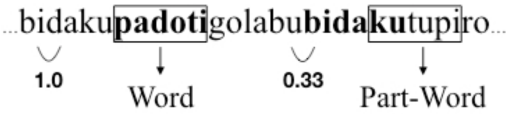

**Figure 1.** Saffran et al (1996). Representation of the continuous stream of nonsense words. In bold some of the conforming words of the stream that had a TP of 1.0 between their syllables. In rectangle an example of a word and a part-word. Part-words were formed by the final syllable of one word and the initial two syllables of another. Internally, they had a dip in TPs compared to words.

This study also inferred that infants needed not to know the words in order to be able to parse them; the presentation of nonsense words discarded prior knowledge of words from their native language as priming effect of word boundaries. Moreover, it has been proven that human adults detect word-like boundaries in a continuous stream of syllable-like musical tones, as well as in visual shapes, indicating that statistical computations are not tied to linguistic input (e.g. Abla, Katahira, & Okanoya, 2008; Fiser & Aslin, 2002; Saffran, Johnson, Aslin, & Newport, 1999).

A study on statistical computations over non-adjacent elements (including syllables, consonants and vowels), in adults demonstrated successful learning over them (Newport & Aslin, 2004). However, another study proved that statistical computations over vocalic segments was extremely difficult and only possible if the stimuli presented was a small subset of words that were repeated extensively (Bonatti, Peña, Nespor, & Mehler, 2005). This thus suggested a degree of functional specialization for statistical computations that depended on linguistic information. That is, the authors claimed that it was precisely the different roles that consonants and vowels play during language processing that leads statistical computations to be more readily performed over consonants than over vowels (see Bonatti et al. 2005).

### 1.1.2 Brain signatures of statistical word segmentation

In auditory language processing one needs to segment the linguistic stream into meaningful words. To this purpose it is important to understand how the brain signals word segmentation in an automatic manner while listening to connected speech. In a study by Sanders, Newport, and Neville (2002), they uncovered that the N100 was acting as an index of word segmentation for nonsense words that participants had just learned. Subjects listened to connected speech containing six nonsense words randomly repeated with no speech segmentation cues. They recorded ERP responses before and after learning the six nonsense words to see what brain responses were elicited by word segmentation and word learning. Results showed that individual differences in performance highly correlated with the N100 word onset amplitude differences before and after training. That is, participants with higher performance increases from before to after training, elicited larger N100 amplitudes after training. Even more, after training, participants elicited an N100 and an N400, this latter component indexing lexical access. These two components suggested that participants effectively learned the words and parsed the stream.

However, Sanders and collaborators' experiment was conducted with the participants directed to pay full attention to the stream of words. In another study, the authors wanted to probe if statistical learning was an automatic process by engaging the participants' attention towards a silent film while listening to the auditory stimuli and recording their ERF/ERP (simultaneous recording with magnetoencephalography –MEG– event-related field and electroencephalography –EEG). Therefore, Teinonen and Huotilainen (2012), presented participants with syllables that could either be part of a trisyllabic pseudoword or random unexpected syllables. Results showed that participants discriminated between random syllables and syllables pertaining to a pseudoword, proving the automaticity of statistical word segmentation (see also Toro, Sinnett, & Soto-Faraco, 2011; Turk-Browne, Jungé, & Scholl, 2005). Moreover, they showed that the N1m (magnetic N1) amplitude seemed to be modulated by the predictability of the syllables in the stream, not by word onset as inferred from previous studies. Amplitude in the N1m was smaller for medial syllables than for initial or final syllables pertaining to pseudowords, thus correlating the level of unpredictability of a syllable with N1m amplitude. Regarding the N400m (magnetic N400), participants elicited larger amplitudes of this component after presentation of unexpected syllables compared to expected syllables. Authors suggested that N1m and N400m reflected statistical segmentation of words at the single syllable level, and showed modulation dependent on the position that the syllables occupied within pseudowords.

This latter study suggests that the N1m and N400m are elicited not only by word onset, and thus signalling word segmentation, but by syllable-level discrimination due to their predictability within the stream dependent solely on their statistical properties. It seems that these components reflect a finer grained analysis of the signal than previously expected. These results are in line with previous results, mentioned above, showing statistical learning in neonates by suggesting that word segmentation was induced by initial and final syllable differences in trisyllabic nonsense words (Teinonen et al., 2009).

### 1.1.3 Brain areas related to statistical learning

There are few statistical learning studies that are conducted using neuroimaging techniques. Areas typically involved in statistical segmentation are the bilateral superior temporal sulcus, the left precentral sulcus and the inferior frontal gyrus (Deschamps, Hasson, & Tremblay, 2016). In a joint ERP-fMRI study, participants listened to a series of streams of connected speech created from a four-nonsense-word artificial language (as in Saffran et al., 1996), and listened to streams of random syllables; then, they had to answer behavioural tests after each stream to determine word learning (Cunillera et al., 2009). Results showed that participants could distinguish between words and part-words. Increased activation in the superior ventral premotor cortex (svPMC) was correlated with subjects' segmentation performance. An N400 component was elicited after a short exposure to the novel nonsense words and identified as an index of speech segmentation. In another study, Karuza et al. (2013) assessed the individual learning performance at different time points by presenting behavioural tests after each four exposures to a stream of connected speech formed by nonsense words. They obtained neural activations that covaried with changes in performance of individual subjects. Results showed that the left inferior frontal gyrus (LIFG) was related to individual statistical learning, and the basal ganglia (BG) participated in the learning process that led to statistical speech segmentation. Moreover, Deschamps et al. (2016) found that inter-individual differences in cortical thickness (CT) over areas associated to statistical learning, attention and memory processes, predicted the ability to detect structures in auditory syllable sequences.

Lopez-Barroso et al. (2013) explored, in a combined diffusion imaging tractography and functional MRI (fMRI) study, whether the strength of structural and functional connectivity between auditory and motor language areas could predict word learning abilities. In particular, they wanted to explore the role that the arcuate fasciculus (AF) plays in word learning. This bundle of nerve fibers connects the temporal and frontal cortices, and patients with lesions on the AF, or its vicinity, have shown impairment in word repetition and verbal short-term memory tasks (Parker Jones et al., 2014). The experiment consisted of a learning phase where a stream of nonsense trisyllabic words were presented with 25 ms pauses between words. These words conformed to an AXC grammar (thus instantiating a non-adjacent regularity between the first and last syllable in each word) and each participant listened to two languages with nine words per language. Participants were instructed to listen carefully and memorize the words. Then, they had to respond in a behavioural recognition test if the word presented was from the stream they heard before (word) or not (non-word, created by scrambling syllables from different languages; see Figure 2A). Results showed that the direct path of the AF is of key importance to word learning, given its participation in auditory-motor integration. In the same vein, the AF was found essential for auditory-motor integration during auditory repetition (Parker Jones et al., 2014).

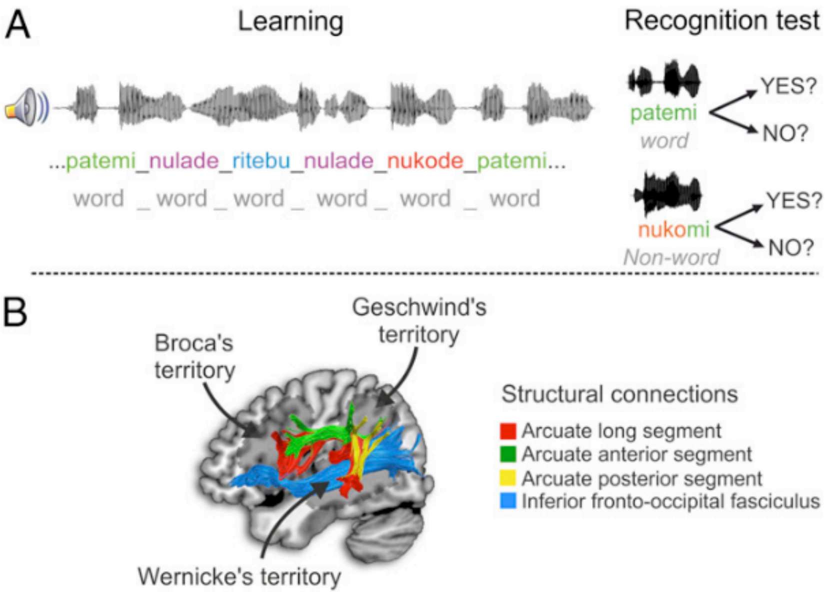

**Figure 2.** Task and methods reproduced from **Lopez-Barroso et al., (2013)**. **(A)** Representation of the word learning task. On the right, the learning phase and, on the left, the recognition test. **(B)** Example of tractography reconstruction of language pathways in the left hemisphere for one of the subjects rendered onto the Montreal Neurological Institute (MNI) template.

## 1.2 Rule Learning

Extracting abstract regularities from a speech stream is of great importance to language acquisition. Speech streams are essentially formed by phonemes that are grouped into syllables, that are grouped into words and phrases and sentences. Understanding the rules that govern speech and learning how to construct words, phrases and sentences obeying them is the essence of grammar and key to language learning. Natural language grammar is very complex and can be studied at different levels. Here, we focus on artificial grammar learning that consists in studies created with a controlled artificial language that possesses a small set of rules and a limited number of lexical items. Specifically, we will focus on a subset of artificial grammar languages called repetition-based grammars, where there is an identity relation between two adjacent or non-adjacent linguistic inputs (mainly syllables or phonemes).

### 1.2.1 Behavioural rule learning studies

The capacity to extract abstract regularities from speech was first seen in the seminal study by Marcus, Vijayan, Bandi Rao, and Vishton (1999). In their study, 7-month-old infants could generalize an abstract regularity placed on adjacent or non-adjacent syllables in a trisyllabic nonsense set of words (ABB rules, B being a repeated syllable and A a different syllable than B, such as *linana*; and ABA rules, such as *gatiga*). Infants were able to discriminate words that followed the same rule that they were familiarized with from foils that violated the rule. These results set the difference between what was considered as statistical computations between syllables, i.e. statistical learning, that is specific to the words being presented in the stream; and the ability to extract algebraic rules from a specific set of words and be able to generalize it to any other new token that followed the same rules. Repetition-based grammars have generated an important number of artificial language learning studies that take as their starting point the study by Marcus and collaborators (1999). Kovács (2014) demonstrated that 7-month-old infants could extract abstract regularities even in the presence of noise (for a recent study with adults, see Monte-Ordoño & Toro, 2018), and these abilities were quite automatic with adjacent repetition-based grammars. For non-adjacent repetition-based grammars the extraction of regularities was dependent on the structure being compared to an identity-based or a diversity-based structure (i.e. an AAB or an ABC grammar, respectively). That is, when ABA patterns were paired with AAB patterns, children only acquired the AAB pattern, while if the ABA pattern was paired with ABC patterns, then they could acquire the ABA pattern. Moreover, these type of grammars have been also tested in non-human animals, such as rats or rhesus monkeys, that show a remarkable ability in successfully extracting and discriminating regularities over adjacent repetitions of the type ABB and AAB, and rats also non-adjacent ABA (Murphy, Mondragón, & Murphy, 2008; for a review, see ten Cate & Okanoya, 2012).

Several studies followed Marcus et al. (1999) indicating that infants and adults are able to extract abstract regularities from a variety of experimentally-controlled grammars. These grammars try to mimic some aspect of natural language grammars, such as the non-adjacent relationship that we see in phrases like "The dog licks her face", where the noun "dog" is tied to the third person suffix "-s" in "lick*s*". In this case, the artificial grammar that mimic this relationship is the AXC grammar, where A and C are the variables with a non-adjacent dependency, while X can take different values. A set of studies on AXC grammars has determined that infants as early as 3 months of age, and adults, can successfully extract regularities over trisyllabic nonsense words, although it is highly dependent on the individual's auditory discrimination abilities. Results also suggest that while infants have the ability to automatically acquire the rule (under passive listening conditions), in adults this ability fades away (Mueller, Friederici, & Männel, 2012). In contrast, studies on repetition-based grammars have been performed on neonates and adults in passive listening and ignored conditions and participants show generalization of the rule (Gervain et al., 2008; Monte-Ordoño & Toro, 2017a, 2017b). However, there seems to be significant individual differences in performance during rule acquisition, and this might be tied to auditory discrimination abilities (Monte-Ordoño & Toro, 2017a). It is interesting to notice, however, that under certain noisy conditions, adults are unable to generalize rules over non-adjacent repetition grammars, while generalization over adjacent repetitions are unaffected by attention demands (Toro, Sinnett, et al., 2011). Taken together, results on these studies point to an automatic mechanism that favours identity-relations that is only triggered by adjacent repetitions (more on this in section 1.3.1., see Endress, Nespor, & Mehler, 2009; Kovács, 2014).

### 1.2.2 Brain signatures of rule learning and rule violation

An important number of studies have explored the neural correlates of abstract rule learning. Some studies have used repetition-based grammars over syllables or phonetic segments in an auditory oddball paradigm (Monte-Ordoño & Toro, 2017a, 2017b; Sun, Hoshi-Shiba, Abla, & Okanoya, 2012b), while other studies have used AXC grammars to uncover the mechanisms of rule and word learning (De Diego Balaguer, Toro, Rodriguez-Fornells, & Bachoud-Lévi, 2007), or the influence of auditory perception, such as the detection of pitch changes, on the extraction of these regularities (Mueller et al., 2012; Mueller, Friederici, & Männel, 2018).

The auditory oddball paradigm is a widely used paradigm to study the electrophysiological responses triggered by rule violations and rule learning. This paradigm consists of the presentation of a stream of frequent stimuli (standards) that follow a certain rule and is interspersed by deviant stimuli that are sporadic stimulus with some physical or abstract characteristic different to the standards. This configuration triggers a mismatch negativity component around 100 and 250 ms when subtracting the grand averages of deviants from standards, signalling a memory trace mismatch generated by the perceived difference between standards and deviants. For instance, in Monte-Ordoño and Toro (2017a), a MMN was elicited after the presentation of deviant stimuli, composed by new phonemes, in a auditory oddball paradigm testing ABB rule learning over vocalic (Vowel condition) and consonantal segments (Consonant condition). The MMN was triggered around 150 ms and was hypothesize to be elicited by the mismatch in phonemic contrasts between standards and deviants.

Another typical component triggered in these tests is related to rule violations. In Monte-Ordoño and Toro (2017b), an auditory oddball paradigm was presented to participants and their electrophysiological responses recorded. A behavioural test was conducted at the end of the experiment. Standard stimuli were CVCVCV nonsense words following ABB rule over syllables. Deviant stimuli had novel phonemes and could be of two types: phoneme deviants, that followed the same abstract rule as standards; and rule deviants, that followed a diversity-based rule (ABC) over syllables. Results showed a P300-like component appearing after rule deviants, denoting rule violation of the abstract rule. Moreover, the amplitude of the component was correlated with the participants' behavioural performance in the rule learning test. Other studies on artificial grammar learning have observed P300-like components after violations of grammatical rules, such as morphological rules (Havas, Laine, & Rodríguez-Fornells, 2017) or vowel harmony violations (Mclaughlin et al., 2010).

In another study, De Diego Balaguer et al. (2007) explored the neural mechanisms underlying rule and word extraction. The authors presented a series of AXC languages, each stream lasting four minutes, and recorded the electrophysiological responses of the participants. The experiment consisted of different phases. There was a learning phase, where only words from the language were presented in the stream. This was followed by a violation phase, where words from the language were interspersed by rule-words (new items that followed the same rule) and non-words (words that had CXA form, thus violating the language's rule) in the stream. A recognition phase at the end of the experiment consisted of a rule learning test, where participants had to choose between rule-words and non-words, and a word learning test, where participants had to choose between words and non-words. These tests assessed participants' ability to learn the words and extract the abstract regularities present in those words and recognize them in new foils. Results showed a P2 component congruent with rule learning that appeared over the third minute of the learning phase. This component was only elicited by participants categorized as good learners, that is, participants that showed high performance scores in the rule learning tests. Also, new foils violating the rule, i.e. non-words, elicited an early frontal negativity (a MMN) and a late posterior positivity (a P600) when analysed in the violation phase, while they elicited an N400 component when presented in isolation in the rule learning test. These results provided evidence of the distinct electrophysiological responses that rule extraction and word extraction generated, therefore regarded as completely separate mechanisms.

Studies in natural grammar processing and artificial grammar learning have been found to activate the frontal operculum (FOP) and the anterior superior temporal gyrus (STG). Particularly, rule violations of adjacent elements were found to active the FOP, and this finding led to suggest that the FOP, connected via uncinate fasciculus to the anterior STG, is the network that supports rule-based grammars (Friederici, 2011).

## 1.3 Constraints in language learning: perceptual constraints

The studies reviewed above have shown that statistical and rule learning mechanisms are very powerful, in the sense that they seem to operate across all ages and over a wide array of stimuli (linguistic and non-linguistic). However, several lines of research have shown that there are clear perceptual constraints that affect the way we process language and extract statistical and abstract regularities from the signal from a very early age. These constraints modulate different aspects of language acquisition and can even modulate learning of certain structures. In the following sections we will review some of them.

### 1.3.1 Primitives that favour perception of certain linguistic structures

It has been reported that adjacent identity elements are easier to detect and process than non-adjacent identity elements in repetition-based grammars (Endress et al., 2009; Gervain et al., 2008; Kovács, 2014). The automatic processing of adjacent relations has been shown to be present already in the neonate brain (Gervain et al., 2008). Endress et al. (2009) proposed that there was a primitive sensitive to identity relations that processed more readily adjacent repetitions. Likewise, the authors showed that another primitive favoured the perception of variables in edge positions. That is, in artificial grammar learning experiments, a repetition implemented over the edge of words, for instance, a word *ABCDEFF* (where each letter represents a syllable) would be easier to detect than if the repetition was implemented in middle positions as in *ABCDDEF*. Hence, two primitives, one sensitive to adjacent repetitions and the other sensitive to sequence edges, would modulate the way we extract information from the linguistic input and may have a role in the way language has been constructed.

### 1.3.2 Linguistic constraints

When it comes to language acquisition, the essential building blocks of language, the phonetic segments, have been seen to have functional differences regarding the extraction of words and rules from a linguistic input. Tracking consonants facilitates word identification, while vowels seem to facilitate the extraction of rule-based grammars (Bonatti et al., 2005; Nespor, Peña, & Mehler, 2003; Toro, Shukla, Nespor, & Endress, 2008). In a series of experiments on continuous streams of CV syllables, Bonatti et al. (2005) demonstrated that the segmentation of a speech stream using statistical information was only possible when tracking transitional probabilities over consonants to segment the stream into words. In contrast, when the statistical regularities were implemented over vowels, the authors did not observe evidence of successful word segmentation. An ERP experiment testing rule learning over consonants and vowels showed that participants used different strategies to acquire rules over consonants than over vowels, accentuating and providing further evidence of the nature of their functional differences in language learning (Monte-Ordoño & Toro, 2017a). These linguistic constraints seem to start operating during the first year of life, as functional differences between consonants and vowels have been reported in young infants during the learning of nonsense words and abstract rules (e.g. Hochmann, Benavides-Varela, Nespor, & Mehler, 2011; Pons & Toro, 2010). Even more, studies with near-infrared spectroscopy have observed different brain responses to items instantiating a pattern over consonants or over vowels even in neonates (Benavides-Varela, Hochmann, Macagno, Nespor, & Mehler, 2012). In contrast, studies with non-human animals do not suggest any functional difference between linguistic segments for other species (e.g. de la Mora & Toro, 2013; Newport, Hauser, Spaepen, & Aslin, 2004). Together, these studies suggest a very early specialization for linguistic segments in humans that guide the discovery of patterns in the signal.

Prosodic cues seem to further modulate word segmentation by statistical cues. Thiessen and Saffran (2003) showed that 9-month-old infants tend to focus more on stress cues than on statistical cues to infer word boundaries. Such result seems to depend on experience with prosodic cues present in the native language, as 7-month-olds seem to do the opposite, that is, to prefer statistical over prosodic cues. Exploring how prosodic and statistical cues are integrated in the adult brain, Cunillera, Toro, Sebastián-Gallés, & Rodríguez-Fornells (2006) showed an increased P2 component when statistical and prosodic cues are combined. This suggested an early integration of this cues. Peña, Bonatti, Nespor, and Mehler (2002) demonstrated that adding subtle pauses between nonsense words implementing an AXC non-adjacent regularity allowed listeners to extract the dependency between A and C syllables (see also Endress & Bonatti, 2007). De Diego-Balaguer, Rodríguez-Fornells, and Bachoud-Lévi (2015) explored how the brain reacted to such cues. In their study, the authors showed that a prosodic cue as simple as including 25 ms pauses inserted between words that followed an AXC pattern, showed an attenuation of the N1 component compared to streams that lacked the prosodic cue. This attenuation was related to the increase in behavioural word learning performance, thus demonstrating that participants changed their segmentation mechanism.

Another interesting bias that seems to modulate how certain regularities are extracted from the signal is related to syntactic categories. Endress and Hauser (2009) showed that, while participants could readily extract repetition-based patterns over non-syntactic categories like animal-animal-clothes, they were unable to learn the rule over syntactic categories, such as noun-noun-verb or verb-verb-noun, if the instances violated syntactic rules. This inability was still present when participants were made aware of their task. Thus, results suggested that human adults' syntactic system imposes an interpretation over streams of nouns and verbs, making it impossible to detect the simpler repetition-based rule over such linguistic structures.

The present dissertation builds on previous studies demonstrating perceptual and linguistic constraints operating over statistical and abstract rule learning mechanisms. This work wants to understand if syllabic structures could pose a similar obstruction to certain basic mechanism of language learning. To understand why we chose the syllable, we will revise, in the following sections, the importance of the syllable in speech segmentation and in language acquisition.

## 1.4 The syllable as a main organizing unit

The syllable has been widely studied and its value to language acquisition has been acknowledged since the seminal study by Mehler (1981), proposing the syllable as the segmentation unit in language. In a series of studies, Segui, Frauenfelder, and Mehler (1981) showed that detection of a syllable composed by two or three phonemes (the target) was easier when this target matched the first syllable of the test word. Participants showed slower reaction times if the target spanned the test word's first syllable. The advantage of the syllable over the detection of phonemes has been shown in other studies were illiterate adults could readily detect and manipulate syllabic segments while failed to do so with phonemes (Morais, Cary, Alegria, & Bertelson, 1979). In the same vein, young infants identify the number of syllables, but not the number of phonemes in a clapping game (Liberman, Shankweiler, Fischer, & Carter, 1974). These results are congruent with more recent studies that suggest that phonemic analysis is an acquired process that requires language learning, while there is an inherent motor-tuning to syllabic rate (Morillon et al., 2010). And is also in line with the stages of language development observed in infants, that exhibit an initial stage of production of syllables present also in deaf infants. It is only later that phonemic production tries to match their caregivers utterances (Morillon et al., 2010). It has thus been proposed that the syllable is the main unit of speech production as well, since infants' ability to break up words into syllable-like chunks appears earlier in life than their ability to break up syllables into phonemes (Wijnen, 1988).

### 1.4.1 The segmentation unit. The N1 and N400.

In a recent study, Räsänen, Doyle, & Frank (2018) proved with a computational model based on the oscillatory entrainment of the brain to speech rhythms, that segmentation of speech into words and syllable-like units is accessible to pre-linguistic infants. Moreover, this model need not any specific language tuning information, thus showing that speech segmentation is available early in life without being constrained by language-related rhythmic classes. Congruent with this study is the ERP experiment run by Teinonen et al. (2009), where neonates were able to readily segment a continuous stream into words by using transitional probabilities to word boundaries. In this study, results showed that newborns could parse the stream by distinguishing initial and final syllables within words by displaying a large negative deflection on the initial syllable, similar to the enhanced negativity shown in the adults' N100 and N400 on the onset syllable of an equivalent segmentation task. Thus, the syllables seem to be the unit allowing the extraction of words and signalling word boundaries in connected speech.

### 1.4.2 Syllabic preference embedded in natural brain oscillations

A recent remarkable finding about the syllable as an organizing unit is related to the way that our brain oscillations are entrained to the rhythms of speech. Studies have shown that the multiple temporal levels at which language is organized are reflected in the entrainment and coupling of different frequency bands that are tracking the distinct hierarchical linguistic structures in speech (Ding, Melloni, Zhang, Tian, & Poeppel, 2016; Giraud & Poeppel, 2012). For instance, the syllabic rate, corresponding to the theta band, is coupled with the phonemic rate, corresponding to the high-frequency gamma band, resulting in a theta-gamma phase-amplitude coupling described by an important neurobiological model (Giraud & Poeppel, 2012). Evidence of brain entrainment to the different hierarchical structures present in speech has been shown not only in MEG studies, but also in an EEG study where entrainment to sentence, phrase, and word/syllable frequencies was produced over English sentences, while a stream of random syllables only elicited entrainment over the syllabic frequency (Ding et al., 2017, 2016). These speech regularities at multiple timescales are entrained to the brain’s rhythmic properties emerging from auditory and motor systems. Interestingly, the natural oscillatory frequency of jaw movements (at 4 Hz) coincides with syllabic rates (Giraud et al., 2007). Moreover, there is a left-right dissociation of the syllabic and phonemic frequencies. Theta fluctuations (corresponding to syllabic frequencies) are best correlated to the right auditory cortex activity, while phoneme frequencies (or gamma band fluctuations) are best correlated with the left auditory cortex activity. Additionally, apart from the left-right dissociation, it is believed that a higher-order temporal integration of phonemic into syllabic segments is taking place in the left auditory cortex. Such integration would reflect syllabic modulation over phonemic rate occurring between the primary auditory cortex (where phonemic oscillatory rates are detected), and the Heschl's gyrus (where syllabic oscillatory rates are detected; Giraud et al., 2007). Together, the behavioural and neurophysiological results suggest that the syllable functions as a key linguistic structure that modulates speech perception and production, and that such functions are rooted in the brain's rhythmic properties.

## 1.5 Aim of the dissertation

In the previous sections, I have shown the importance of two mechanisms involved in language acquisition that are present in humans since birth: statistical learning and rule learning. Statistical learning is the mechanism that helps us parse a speech signal into words by using transitional probabilities between syllables. Rule learning is the mechanism that allows us to extract regularities from the language in order to understand the hierarchical relations that exist between its constituents. We have also mentioned the importance of the syllable as a linguistic unit, for its role in speech segmentation and its relevance in speech perception and speech production.

The present dissertation aims at exploring if an important unit in language, i.e. the syllable, could modulate rule learning over repetition-based grammars, and the extraction of words during statistical word segmentation as other linguistic units (including phonetic segments and syntactic categories) seem to do.

In Chapter 2 of the present dissertation, we will present a series of behavioural experiments exploring the extraction of regularities from a stream of nonsense words following an adjacent repetition-based grammar (ABB) implemented over syllables and over vowels. In order to determine the role that syllabic structure plays in the extraction of such regularities, each experiment will test a different change in syllabic structure from familiarization to test, from very frequent structures (such as CV) to infrequent structures (such as CCV) in the Spanish language. As a baseline to compare changes in performance found in the previous experiments, an additional experiment that does not incorporate a change in syllabic structure will be presented. This series of experiments on generalization of abstract rules will be complemented by a series of experiments on statistical learning. In these experiments a continuous speech stream with no pauses that comprises four nonsense words is presented. Through a series of experimental modifications, we will explore if a change in syllabic structure interferes with the discrimination of the words parsed from a continuous speech stream.

In Chapter 3, we present two experiments following an auditory oddball paradigm where we register the participants' electrophysiological responses after violations of an abstract rule. The aim of these experiments is to explore the brain components elicited after a change in syllabic structure during the generalization of an abstract repetition-based rule. In Experiment 1, we present words that follow an adjacent repetition-based grammar (e.g. ABB) over syllables. In Experiment 2, we present words that follow a non-adjacent repetition-based grammar (e.g. ABA) over syllables.

The focus of both experiments is to observe the reactions triggered by changes in the abstract rule and the syllabic structure presented to the participants. We also discuss the main differences that following rules over adjacent and non-adjacent rules can generate.

Chapter 4 summarizes the main results encountered in our behavioural and electrophysiological experiments, discusses in more detail key results we observed, describes the possible lines for future research that can be followed, and presents the conclusions we can draw from our studies.

# Chapter 2

# Syllabic Structure Interference in Rule Learning and Statistical Learning

In this section, we will explore if participants can generalize an abstract adjacent repetition-based grammar and discriminate the nonsense words present in a continuous stream when there is a change in syllabic structure. That is, we will determine if rule learning and statistical learning mechanisms can be obstructed by changing the linguistic unit over which they operate, the syllable.

## 2.1 Introduction

In order to learn a language, research says that we use two basic mechanisms to discover its structure: (1) Statistical learning, a mechanism that helps us compute the transitional probabilities between syllables in a continuous stream to parse it into words, and (2) Rule learning, a mechanism that helps us keep track of the regularities in the stream in order to create a hierarchical map that groups syllables into words, words into sentences, and so on. Therefore, there is a specialized mechanism–namely statistical learning–that transforms an unintelligible continuous stream in a parsed stream of words, and there is an abstract mechanism–namely rule learning–that tracks abstract rules in the stream to organize it into hierarchical intelligible information (Marcus et al., 1999; Peña et al., 2002; Saffran et al., 1996; Toro, Nespor, Mehler, & Bonatti, 2008).

In the literature, we find an important number of artificial grammar learning studies focusing on the learnability and extraction of regularities over syllables. These studies have used a wide variety of artificial grammars to understand how we extract information from language at different hierarchical levels. From simple grammars, such as repetition-based grammars (ABB or ABA; e.g. Kovács, 2014; Marcus, 1999; Monte-Ordoño & Toro, 2017b), to more complex grammars, such as AXC grammars (e.g. de Diego Balaguer, Toro, Rodriguez-Fornells, & Bachoud-Lévi, 2007; Mueller, Bahlmann, & Friederici, 2010; Mueller, Oberecker, & Friederici, 2009), complex grammatical rules implemented in a miniature version of a language (Mueller, Girgsdies, & Friederici, 2008), or the use of finite-state grammars (Morgan & Newport, 1981). In the present study, we decided first to focus on the learnability of simple abstract repetition-based rules, as they have been claimed to provide a good approximation to the basic structures that might underlie grammar processing (e.g. Marcus et al., 1999). Studies exploring the conditions under which abstract linguistic rules might be learned focus on the generalization of token-independent patterns that define a set of words. Complementarily, we also studied statistical learning mechanisms. In statistical learning, the frequency of co-occurrence between syllables is used to parse the stream into words. By computing transitional probabilities (TPs) between syllables we can extract and discriminate words in the stream. In order to explore how these TPs work, statistical learning experiments are based on artificial languages that contain few words and are presented as a stream of syllables with no prosodic cues and no pauses. Therefore, the only way to parse the stream is by using the TPs between syllables. Saffran et al. (1996), tested a group of 8-month-old infants in a statistical learning paradigm. The authors invented an artificial language composed of 4 trisyllabic CVCVCV nonsense words. All of the words in this language would hold the same TPs within words and between words. For instance, the nonsense word *bidaku*, would have a TP of 1 between *bi* and *da,* and between *da* and *ku,* because only *da* could follow *bi*, and only *ku* could follow *da*. And would have a TP of 0.33 between *ku* and the first syllable of one of the three other words conforming the language. Results showed that they discriminated words in the language from part-words (words created from the two last syllables of one word and the first syllable of another word, therefore part-words had lower TPs than words in the language).

Given their importance for language learning, an interesting avenue of research has explored how basic computational mechanisms interact with linguistic knowledge. Several lines of research have shown that in fact linguistic representations modulate the way listeners extract patterns from the speech signal. Regarding the learning of abstract rules, for example, listeners display what has been called "pattern deafness". This is a difficulty to learn simple rules if they are instantiated over syntactic categories (nouns and verbs), but the elements in the sequence are organized in syntactically impossible orders (e.g. verb-verb-noun; Endress & Hauser, 2009). In parallel, the different roles that consonants and vowels seem to play during language processing (for a review, see Nazzi, Poltrock, & Von Holzen, 2016) can be reflected in the way general learning mechanisms operate over consonants and vowels, as these phonetic categories are the preferred targets of separate computations. Studies have found that distributional dependencies are predominantly computed over consonants (Bonatti et al., 2005), while simple rules are preferentially extracted from vowels (Toro et al., 2008; Toro, Shukla, Nespor, & Endress, 2008). Even more, difficulties to generalize rules over consonants are observed even before the first year of life, and much before a complete lexicon is in place (Hochmann et al., 2011; Pons & Toro, 2010). Similar linguistic constraints seem to modulate the operation of statistical learning mechanisms. Finn and Hudson Kam (2008) showed that English speakers did not prefer nonsense words over foils when these words began with a consonantal cluster that violated phonotactic rules in English (e.g. /tfobu/). In their study the authors presented participants with a stream of nonsense words containing either valid (control group) or invalid (experimental group) English onsets. While participants in the control group correctly segmented the stream, participants in the experimental group did not. Results thus showed that the presence of word onsets violating phonotactic rules prevented participants from correctly segmenting the stream using statistical computations, as linguistic knowledge interfered with the extraction of distributional information. Similarly, Toro, Pons, Bion, and Sebastián-Gallés (2011) showed that the violation of a word-forming rule in Catalan (the presence of more than one mid vowel within a word) may interfere with word extraction by statistical computations. Catalan native adult participants were presented with a continuous speech stream composed of trisyllabic nonsense words that violated this linguistic constraint. In a subsequent test, participants did not recognize the words from matched foils. Nevertheless, the same words were recognized if the test comprised foils that never appeared during familiarization, or if both words and foils were presented visually. However, to the best of our knowledge, there is no systematic study of how these basic computational processes might be modulated by the basic processing unit in language, that is, the syllable.

The role of the syllable in language is very important and has been seen in different behavioural studies. In a seminal study, Mehler, Dommergues, Frauenfelder, & Segui (1981) showed that participants could readily detect a target, which was a syllable composed of two or three phonemes, if the target matched the first syllable of the tested word. If the target spanned or was shorter than the syllable, participants had slower reaction times. This study reflected the pre-eminent role the syllable has, even over phonemic segments (see also Pallier, Sebastian-Gallés, Felguera, Christophe, & Mehler, 1993). In another study, illiterate adults could easily detect and manipulate syllables, while failed to do so with phonemic segments (Morais et al., 1979). Additionally, Cutler, Mcqueen, Norris, and Somejuan (2001), considered that the syllable had a language-universal role since several studies showed evidence that any size and any type of syllable could be seen as a viable parse in lexical segmentation. The authors suggested that it did not matter the phonotactic constraints of the language, or if the language did not consider that syllable as a possible word. When parsing a speech stream, if the portion of speech was syllabic, it would be favored and easier to segment (and spot a word) for listeners than when the portion was not syllabic (e.g. a consonant or a stream of consonants). Even preverbal infants prefer the use of syllable-like chunks to parse a continuous stream (Räsänen et al., 2018). Thus, in a seminal paper, Mehler (1981) described the syllable as the *basic* *processing unit of speech*, used to segment the signal and access the lexicon.

These behavioural studies are supported by more recent studies on the neural entrainment of brain oscillations to speech streams. Luo and Poeppel (2012) showed that there are two cortical temporal scales at which the neuronal oscillations phase-lock in a speech signal: a longer one, corresponding to a timescale of ~200 ms (associated oscillatory frequency at the theta band: 4~8 Hz), and a shorter one, corresponding to a timescale of ~25 ms (associated to the low gamma band: 38~42 Hz). The longer timescale corresponds to the syllable mean duration, and the shorter timescale to the phoneme or segment duration. Interestingly, another study by Luo and Poeppel (2007) proved that it is the syllable rate that plays a critical role for spoken language recognition, since intelligibility of speech just requires modulation frequencies below 16 Hz not to be altered. In other words, the brain processes two main timescales in the speech stream: at the syllabic and at the phonemic level. Each timescale provides unique information about the speech stream, and it is at the syllabic modulation frequency that the speech is essentially detected as such.

Given the importance the syllable seems to have in speech processing, in this study we tested if syllabic structures interfered with basic language learning mechanisms, such as rule learning and statistical learning. In the rule learning experiments, a series of 4 experiments (Experiment 1 to 4) tested if participants could extract an ABB rule over syllables (Syllable Condition) or over vowels (Vowel Condition). We decided to test rule learning only over vowels because consonants facilitate the segmentation of the stream and word learning, while vowels facilitate the extraction of grammatical rules (Bonatti et al., 2005; Nespor, Peña, & Mehler, 2003; Toro et al., 2008). That is, consonants are not good candidates for rule learning, and actually human adults, with a brief familiarization, are able to extract rules based on vowels but not based on consonants (Toro et al., 2008). Due to these functional differences between consonants and vowels, we opted to test syllabic interference in rule learning over vowels and not over consonants. Participants were presented with trisyllabic nonsense words with a given syllabic structure (e.g. CVCVCV or CVCCVCCVC) on the familiarization phase and then were tested with a different syllabic structure on the test phase (e.g. CCVCCVCCV). Importantly, Experiment 4 was a control condition, where no syllabic structure change occurred between familiarization and test. Performance of participants in this control condition was used as baseline for comparisons from Experiments 1 to 3. In Experiment 5, participants were tested in a statistical learning paradigm, were they heard a continuous speech stream containing 4 CVCVCV nonsense words and then were tested with these same words with a modified syllabic structure (e.g.

CCVVCV). Experiment 5 included two control conditions; one condition with no change in syllabic structure (No Change Condition) and the other condition to verify that participants were not 'deaf' to syllabic structure (Test Control Condition). We hypothesize that, if syllabic structure is modulating rule learning and statistical learning, then a change in syllabic structure of the stimuli from the familiarization phase to the test phase will hinder the ability to learn the rule or to segment the speech stream. If, on the contrary, these processes are not modulated by syllabic structure, performance of the participants will not differ from the condition where no change in syllabic structure has been applied between familiarization and test.

## 2.2 Experiment 1 – Changing structures (CV to CVC)

In this experiment we tested whether changing the structure of the syllables from familiarization to test would affect the participants' ability to recognize an abstract rule. The experiment had 2 conditions. In the Syllable Condition the target ABB rule was implemented over syllables composing the nonsense words. However, effects of changes in syllabic structure might be more salient if the focus of the rule-extraction process is focused on the nucleus of the syllable. So the experiment also included a Vowel

Condition in which the rule was implemented only over the vowels of the words.

### 2.2.1 Methods

#### *Participants*

Participants were 34 adult volunteers. Half of them (N=17) were assigned to the Syllable Condition (10 females, mean age: M=24.06, SD=5.34) and half to the Vowel Condition (13 females, mean age: M=24.24, SD=8.90). All participants were either native Spanish speakers, or highly proficient Spanish speakers. They received payment as compensation for their participation in the study.

#### *Stimuli*

We created 36 CVCVCV trisyllabic nonsense words for the familiarization phase and 16 CVCCVCCVC trisyllabic nonsense words for the test phase. CV and CVC syllables were recorded by a native Spanish female speaker in a sound-attenuated booth. The female speaker read each syllable in a two-syllable word, the first syllable always being ‘PA’. Stress was placed always on the first syllable. Target syllables were then selected and extracted. Syllables were normalized to an intensity of 70 dB, fundamental frequency of 215 Hz and duration of 340 msec or 390 msec (for CV and CVC, respectively) using Praat (www.praat.org). To create the CV syllables we used vowels /e/, /i/ and /o/, and consonants /f/, /m/, /b/,

/d/ and /t/. A total of 15 CV syllables were created. To create the CVC syllables we used different phonemes from those used to create the CV syllables. We used vowels /a/ and /u/, and consonants /r/, /p/, /g/, /l/, /n/ and /k/. A total of 18 CVC syllables were created. They all followed legal Spanish phonotactics. The CVC syllables started with the phonemes /p/, /g/ or /k/, and ended with the phonemes /r/, /l/ or /n/, creating syllables such as *pur*, *gal* and *cun*.

In the Syllable Condition, we combined CV syllables to create 36 nonsense trisyllabic words to use during familiarization. Syllables in these words were always arranged following an ABB rule (so, the second syllable on each word was repeated), forming words such as *mebobo, fitete* or *difofo* (see Annex 1, Table 1). For the test phase, we combined CVC syllables to create 16 novel nonsense trisyllabic words. Eight of these words (from now on *rule words*) followed the same ABB rule as words presented during familiarization (e.g. *palgungun, canpurpur* or *guncalcal*). No syllable was repeated within each word in the remaining 8 words (from now on *non-rule words*), creating words such as *cangulpar, carpungal* or *pulcargun*.
In the Vowel Condition, we combined CV syllables to create 36 nonsense trisyllabic words to use during familiarization. Vowels in these words followed an ABB rule. No consonant was repeated within each word, creating items such as *febiti, bimodo* and *domebe.*

As in the Syllable Condition, 16 CVCCVCCVC test items were created (8 rule words and 8 non-rule words). In the rule words, vowels followed the ABB rule and consonants varied with no repetitions (e.g. *palguncur, cargulpun* or *guncalpar*). The non-rule words were the same ones used in the Syllable Condition, so no syllable was repeated within each word (see Annex 1, Table 3).

### *Apparatus*

Participants ran the experiment individually in a sound-attenuated booth. The experiments were run using Psyscope X B77 (http://psy.ck.sissa.it/) on an iMac with operative system X Yosemite version 10.10. Participants read the instructions on the screen and listened to the stimuli over headphones (JVC HAS160W).

### *Procedure*

The experiments had a familiarization phase and a test phase. In the familiarization phase participants were presented with trisyllabic CVCVCV nonsense words. Thirty-six words were repeated 3 times in random order with pauses of 500 ms between words. The duration of the familiarization phase was approximately 3 minutes. After the familiarization, there was a test phase. During the test phase, participants were presented with pairs of trisyllabic CVCCVCCVC nonsense words. Words were presented in a two-alternative forced choice test (2AFC). There were 8 test trials. In each test trial a rule word and a non-rule word were played with a

500 ms pause between them. Order of presentation of the rule word and the non-rule word was counter-balanced across test trials. Participants were asked to choose the word that sounded more similar to the words heard during familiarization. Participants were told that they could answer at their own pace.

### 2.2.2 Results

In the Syllable Condition, participants generalized the ABB rule when the syllabic structure was changed from CVCVCV, in the familiarization phase, to CVCCVCCVC in the test phase (M=90.44, SD=3.79), with performance being significantly above chance (t(16)=10.66, p<.001). In the Vowel Condition, participants' performance was also significantly above chance (M=60.29, SD=4.04; t(16)=2.55, p<.05). A two-sample t-test comparing performances across conditions yielded significant differences between them (t(32)=5.44, p<.001), suggesting it was easier for the participants to extract the rule over the syllables than over the vocalic segments.

## 2.3 Experiment 2 – Familiarizing with CVC

Results from Experiment 1 show that participants correctly generalize an abstract rule even though the syllabic structure of the words instantiating the rule changes from familiarization to test. However, CV syllables are the most common one in Spanish, which is the native language of the participants (Sandoval, Toledano, Curto, & De La Torre, 2006). To be sure the generalization across syllabic structures is found independently of the frequency of the specific syllables used during familiarization, in Experiment 2 we familiarized participants with words composed by CVC syllables and tested them with words composed by CV syllables.

### 2.3.1 Methods

#### *Participants*

Thirty-four adult participants were included in the study. Half of them (N=17) were assigned to the Syllable Condition (14 females, mean age: M=21.0, SD=1.41) and the other half to the Vowel Condition (13 females, mean age: M=24.18, SD=5.33). All participants were native Spanish speakers and received payment as compensation for taking part in the study.

### *Stimuli*

We created 36 CVCCVCCVC trisyllabic nonsense words for the familiarization phase and 16 CVCVCV trisyllabic nonsense words for the test phase. CVC and CV syllables were recorded by the same female speaker and then normalized using the same acoustic parameters as in Experiment 1. To create the CVC syllables for the familiarization we used the vowels /e/, /i/ and /o/ and the consonants /n/, /r/, /p/, /g/, /l/ and /k/. Forty-five syllables were created following legal Spanish phonotactic constraints and never repeating a consonant in the same syllable. Initial phonemes in each CVC syllable could be /p/, /g/ and /k/, while final phonemes could be /n/, /r/ and /l/, forming syllables such as */nel, /gon/* and */pir/*. To create the CV syllables for the test phase we used different phonemes than those used for CVC syllables. We used vowels /a/ and /u/, and consonants /f/, /m/, /b/, /d/ and /t/. Ten CV syllables were created by the combination of these phonemes (e.g. */fa/*, */mu/* and */du/*).

In the Syllable Condition, 36 trisyllabic nonsense words were created for the familiarization phase by combining CVC syllables. Syllables were organized following an ABB rule, creating items such as *nergilgil, rolcencen* and *cinlerler.* For the test phase, 16 CVCVCV trisyllabic words were created, 8 rule words and 8 non-rule words. Rule words followed the same ABB rule as the words used during familiarization, such as *fabubu, mutata* and *datutu*. On the contrary, no syllable was repeated within the remaining test words (non-rule words, e.g. *famuba, matuda* and *dubatu*, see Annex 1, Table 2 and 4).

In the Vowel Condition, 36 nonsense trisyllabic words were created for the familiarization phase by combining CVC syllables where vowels followed an ABB rule, while no consonant was repeated within each word (e.g. *gencirpil, pelcingir* and *goncelper*). As in the Syllable Condition, 16 CVCVCV test items were created (8 rule words and 8 non-rule words). Vowels in the rule words followed an ABB rule as vowels in the familiarization phase (e.g. *batudu, tamubu* and *mufada*). Non-rule words were the same as in the Syllable Condition, so vowels did not follow the same rule as in the familiarization phase (see Annex 1, Table 8 and Table 10).

#### *Apparatus and Procedure*

The apparatus and procedure were the same as in Experiment 1.

### 2.3.2 Results

Participants' performance was significantly above chance in the Syllable Condition (M=80.88, SD=5.26; t(16)=5.87, p<.001) and in the Vowel Condition (M=57.35, SD=3.40; t(16)=2.16, p<.05), however, differences between conditions were significant (t(32)=3.76, p<.001). The results show that participants could extract the ABB rule over syllables and over vowels even though the syllabic structure was modified from CVCCVCCVC in the familiarization phase to CVCVCV in the test phase.

## 2.4 Experiment 3 – Switching to less frequent structures (CV to CCV)

We decided to run one final test to be sure that rule generalization across syllabic structures is independent of the specific structures used. We thus tested generalization to CCV syllables that are valid in Spanish but occur less frequently than CV and CVC syllables (Sandoval et al., 2006).

### 2.4.1 Methods

#### *Participants*

Participants were 34 adult volunteers. Half of them (N=17) were assigned to the Syllable Condition (11 females, mean age: M=23.65, SD=4.90) and half to the Vowel Condition (11 females, mean age: M=24.77, SD=7.48). All participants were either native Spanish speakers or highly proficient Spanish speakers. Participants received payment for taking part in the study.

### *Stimuli*

For the familiarization phase we used the same 36 CVCVCV trisyllabic nonsense words from Experiment 1. Sixteen CCVCCVCCV trisyllabic nonsense words were created for the test phase. CCV syllables were recorded by the same female speaker and then normalized using the same acoustic parameters as in Experiments 1 and 2. CCV syllables had the same duration as CVC syllables. CCV syllables were created using novel phonemes not used in the familiarization phase: vowels /a/ and /u/, and consonants /k/, /p/, /g/, /l/ and /r/. Phonemes were combined taking into account the Spanish phonotactic constraints. Therefore, initial phonemes in the CCV syllables were /k/, /p/ and /g/, while final phonemes were /l/ and /r/, forming syllables such as */cra/*, */plu/* and */gla/.*

In the Syllable Condition, we used the same 36 CVCVCV trisyllabic words used in the familiarization phase of the Syllable Condition in Experiment 1. For the test phase, eight rule words were created following the same ABB rule as during familiarization (e.g. *pragluglu, claprupru* and *gruplapla*). Eight non-rule words were created containing no syllable repetition (e.g. *praclugra, glucraplu* and *plugraclu,* see Annex 1, Table 5).

In the Vowel Condition, we also used the same 36 CVCVCV trisyllabic words used in the familiarization phase of the Vowel

Condition in Experiment 1. For the test phase, eight rule words that followed an ABB rule on vowels were created (e.g. *praglucru, cruglapra* and *plucragla*). Non-rule words were the same as in the Syllable Condition (see Annex 1, Table 11).

#### *Apparatus and Procedure*

The apparatus and procedure were the same as in Experiments 1 and 2.

### 2.4.2 Results

As in previous experiments, participants' performance was significantly above chance in both conditions. Participants extracted the rule over the syllables (M=77.21, SD=5.05; t(16)=5.38, p<.001) and over the vowels (M=61.77, SD=3.79; t(16)=3.11, p<.01) when the syllabic structure changed from CVCVCV in the familiarization phase to CCVCCVCCV in the test phase. As we observed in Experiments 1 and 2, performance in the Syllable Condition was higher than in the Vowel Condition (t(32)=2.45, p<.05).

## 2.5 Experiment 4 – No change in syllabic structure

Results from Experiments 1 to 3 show that listeners generalize an abstract rule across different syllabic structures. However, we need to have a comparison condition in which there is no change in syllabic structure to assess if such changes tax in any way the rule learning process. Thus, in Experiment 4 we familiarized and tested participants with nonsense words composed by CV syllables.

### 2.5.1 Methods

#### *Participants*

Thirty-four adult participants volunteered for the study. Half of them (N=17) were assigned to the Syllable Condition (11 females, mean age: M=21.82, SD=2.10) and the other half to the Vowel Condition (14 females, mean age: M=20.71, SD=1.61). Four participants were discarded for not following the instructions. All participants were native Spanish speakers and received payment for taking part in the study.

#### *Stimuli*

For the familiarization phase we used the same 36 CVCVCV trisyllabic nonsense words from Experiment 1 and 3. Sixteen CVCVCV trisyllabic nonsense words were created for the test phase. We used novel phonemes to create the test words: vowels /a/, /u/, and consonants /n/, /r/, /p/, /g/ and /l/ to create a total of 10 syllables (e.g. */pa/, /gu/* and */ra/*).

In the Syllable Condition, the same 36 CVCVCV trisyllabic words as in the Syllable Condition of Experiments 1 and 3 were used for the familiarization phase. For the test phase, 16 CVCVCV trisyllabic nonsense words were created. Eight rule words followed the same ABB rule as during familiarization (e.g. *naruru, nupapa* and *gunana*). Eight non-rule words were created so that syllables were all different within the word (e.g. *napura, galupa* and *runalu,* see Annex 1, Table 6).

In the Vowel Condition, the same 36 CVCVCV trisyllabic words as in the Vowel Condition of Experiments 1 and 3 were used for the familiarization phase. For the test phase, 16 CVCVCV trisyllabic nonsense words were created (8 rule words following the ABB rule on the vowels, such as *narupu, nurala* and *gunapa*; 8 non-rule words that were the same as in the Syllable Condition, see Annex 1, Table 12).

#### *Apparatus and Procedure*

The apparatus and procedure were the same as in Experiments 1 to 3.

### 2.5.2 Results

Participants' performance was significantly above chance for the Syllable Condition (M=80.15, SD=4.92; t(16)=6.13, p<.001) and for the Vowel Condition (M=65.44, SD=4.36; t(16)=3.54, p<.01). Differences between Conditions were significant (t(32)=2.24, p<.05). A two-way ANOVA, using as between-subjects factors

Experiment (1 to 4) and Condition (Syllable, Vowel), yielded a main effect of Condition (F(1,128)=45.90, p<.001). No other effect or interaction was significant. Thus, from Experiments 1 to 4 we observed that performance in a rule learning task is not taxed when syllabic structure changes from familiarization to test. Participants learned and generalized the underlying abstract rule equally well when there was a change in syllabic structure (Experiments 1 to 3) and when there was no change at all (Experiment 4).

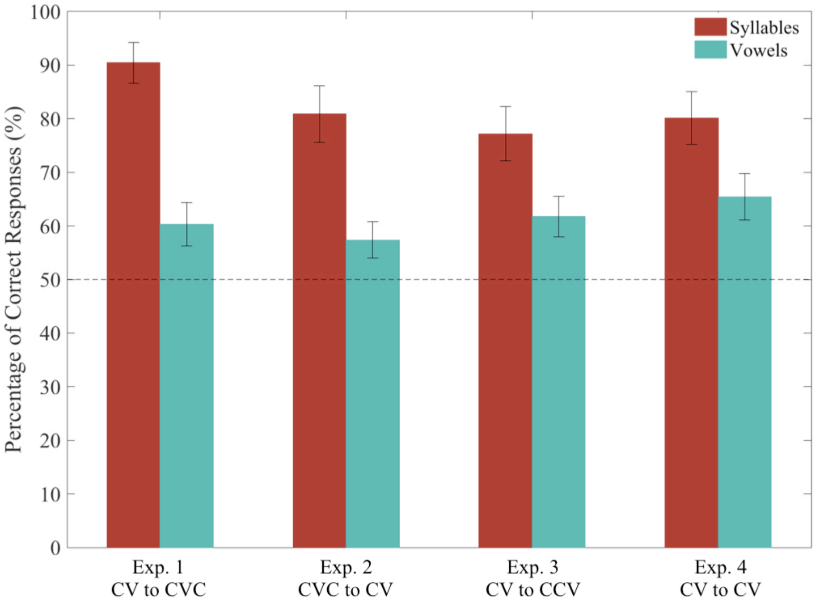

**Figure 3.** Experiments 1 to 4 – Rule learning. Bar graph of the average performance in each experiment and condition. From left to right, results from Experiment 1 to 4 intercalating Syllable and Vowel condition results. Dashed line indicates chance level and error bars indicate standard error (SE).

## 2.6 Experiment 5 – Changing structures over statistical regularities

The operation of extracting abstract rules has been claimed to be token-independent. That is, what matters is the relationship between different elements independently of the specific elements that actually instantiate the rule (see Marcus et al., 1999)). Results from our previous experiments seem to confirm that participants in fact generalize the abstract rule independently of the structure of the syllables that instantiate it. Thus, syllabic structure does not seem to modulate rule learning. However, syllabic structure might modulate the extraction of statistical regularities that are more tightly linked to the specific elements over which they are created. In Experiment 5 we tested this possibility.

### 2.6.1 Methods

#### *Participants*

Participants were 51 adult volunteers. A third of the participants (N=17) were included in the Change Condition (13 females, mean age: M=21.41, SD=3.43), a third (N=17) in the No Change Condition (14 females, mean age: M=21.0, SD=4.12), and the remainder of the participants (N=17) in the Test Control Condition (11 females, mean age: M=21.11, SD=1.58). Five participants were discarded for not following the instructions. All participants were either native Spanish speakers or highly proficient Spanish speakers. Participants received payment for taking part in the study.

### *Stimuli*

We created 4 CVCVCV trisyllabic nonsense words for the familiarization phase and 8 trisyllabic nonsense words for the test phase. CV, CCV and V syllables were recorded by the same native Spanish female speaker as in Experiments 1 to 4. CV and CCV syllables were normalized to the same acoustic parameters as in previous experiments. V syllables were normalized at a duration of 720 msec, and pitch (215 Hz) and intensity (70 dB) were the same as the other syllables. For the familiarization phase in all three conditions we used the nonsense words *furebo, golune, carimu* and *pelati*. Words were concatenated with no acoustic pauses between them. Syllables within each word had a transitional probability (TP) of 1. TPs between words were set to 0.33 (so each word could be followed by any of the remaining 3 words).

For the Change Condition, we created 8 trisyllabic nonsense words for the test phase. Four of the words had a CCV V CV structure (from now on *tp-words*), and four had a CV CCV V structure (from now on *part-words*). Tp-words were created by changing the syllabic structure of words used during familiarization from CVCVCV to CCVVCV. For example, the word *golune* would become *gloune*. Thus, Tp-words have the same TPs among segments than words used during familiarization, but their syllabic structure is different. Part-words were created by putting together the last syllable from one of the tp-words and the two first syllables from another. This created part-words such as *muplea* (resulting from *craimu* and *pleati*) and *tiglou* (resulting from *pleati* and *gloune*). TPs among segments in part-words dropped to 0.33 between the first and second syllables. So, both types of test items (tp-words and part-words) were different from familiarization words in their syllabic structure. However, tp-words had TPs of 1 among segments, while part-words included a dip in TPs.

For the No Change Condition, we created 8 CVCVCV trisyllabic nonsense words for the test phase. Four of the test items were the same words used during familiarization (*golune, carimu, pelati* and *furebo*). Four part-words were created by combining the last syllable of one of the words with the first two syllables of another word, creating items such as *bocari* and *mupela*. Both types of test items (words and part-words) would have the same syllabic structure of the familiarization phase. Words differed from part-words only in their TPs.

For the Test Control Condition, we created 8 trisyllabic nonsense words for the test phase. We pitted words against tp-words. The four words were the same items used in the No Change Condition and the familiarization phase (*carimu, golune, furebo* and *pelati*).

The four tp-words were the same items used in the Change Condition (*craimu, gloune, fruebo* and *pleati*). Both types of test items (words and tp-words) were composed by the same segments arranged in the same order. The only difference between words and tp-words was that words had the same syllabic structure as items during familiarization (CVCVCV) while tp-words had a different syllabic structure (CCVVCV).

### *Apparatus*

We used the same apparatus as in Experiments 1 to 4.

### *Procedure*

The experiment had a familiarization phase and a test phase. In the familiarization phase participants were presented with a continuous speech stream composed by the 4 CVCVCV trisyllabic nonsense words. The duration of the familiarization phase was approximately 3 minutes. In the test phase, participants were presented with a 2AFC. There were 8 test trials pitting test items depending on condition (Change Condition: tp-words vs part-words; No Change Condition: words vs part-words; Test Control Condition: words vs tp-words). There was a 500 ms pause between test items. Order of presentation of type of items was counter-balanced across trials. Participants were asked to choose the word that sounded more like the words they heard during familiarization.

### 2.6.2 Results

In the Change Condition, participants successfully segmented the stream (M=58.82, SD=2.79; t(16)=3.17, p<.01). We also observed above-chance segmentation performance when there were no changes in syllabic structure (No Change Condition; M=62.50, SD=4.67; t(16)=2.68, p<.01) and when words that were actually presented during familiarization were pitted against their syllabic change equivalents (Test Control Condition; M=88.97, SD=2.60; t(16)=14.99, p<.001). An ANOVA comparing performance across conditions (Change, No Change, Test Control) yielded significant differences between them (F(2,48)=22.32, p<.001). Pairwise comparisons showed there were no differences in performance when there was a change in syllabic structure from familiarization to test (Change Condition) and when there were no changes in syllabic structure (No Change Condition; p=1). Thus, participants correctly recognize statistically-coherent sequences of phonemes, independently of syllabic structure. That is, statistical learning does not seem to be taxed by changes in syllabic structure. However, performance in the Test Control Condition was significantly higher than that observed in the Change Condition (p<.001) and in the No Change Condition (p<.001). So participants were not *deaf* to syllabic structure. They could readily tell apart the words that were presented during familiarization from the same sequence of phonemes with a modified syllabic structure. During test, they preferred the words they have actually heard (word test items) to words they have not heard before (tp-word test items). Nevertheless, when participants are presented with a choice between two test items with a different syllabic structure from familiarization (Change Condition), they correctly use the statistical information defining phoneme sequences to the point that their performance is no different to that observed when there are no changes in syllabic structure (No Change Condition).

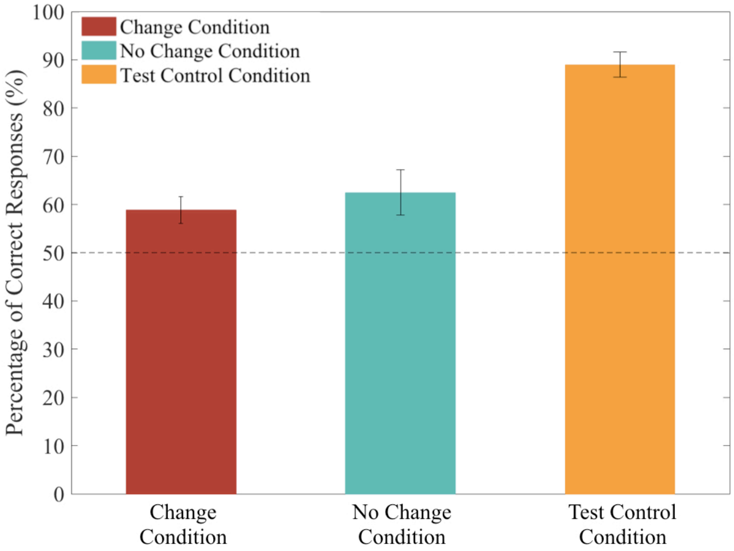

**Figure 4.** Experiment 5 – Changing Structures over Statistical Regularities. Bar graph of the average performance of participants in each condition. Dashed line indicates chance level and error bars indicate SE.

## General Discussion

In the first four experiments we sought to determine if a syllabic structure could interfere with learning abstract rules at the syllabic and the segmental (vocalic) level. In the familiarization phase, participants were presented with CVCVCV trisyllabic nonsense words (Experiments 1,3 and 4) or CVCCVCCVC nonsense words (Experiment 2). These words followed an ABB rule on syllables (Syllable Condition) or on vowels (Vowel Condition). In the test phase, the generalization of the rule was evaluated with new nonsense words constructed with a different syllabic structure. In Experiment 1, we used CVCCVCCVC nonsense words, in Experiment 2, CVCVCV words, in Experiment 3, CCVCCVCCV words, and in Experiment 4, CVCVCV words (Control Condition). The results show that participants generalized the adjacent repetition-based grammar ABB over syllables and over vowels. Further analysis, comparing all the experiments, determined that participants were better at detecting rules over syllables than over vowels. This suggests that rule extraction over linguistic stimuli is not dependent on specific instances conforming the syllable, as vowels, but is preferentially performed over the syllable as a unit *per se*. In Experiment 5, we explored the possibility that syllabic structure could interfere with statistical learning. In a series of three experiments we showed that syllabic structure did not interfere with statistical learning. Participants recognized and showed preference for words heard during the familiarization phase over the same words with a modified syllabic structure. That is, participants expressed word learning and the ability to discriminate between the original words presented in the familiarization and their syllable-modified counterparts.

### 2.6.3 On Rule learning

Our results show that syllabic structure does not interfere with ABB rule learning. Endress, Nespor, and Mehler (2009) hypothesized of the existence of an automatic perceptual mechanism sensitive to identity relations that gives advantage to adjacent repetitions. Thus, automatic processes entail ease of processing. It is possible that adjacent repetition-based grammars are very easy to process and, therefore, a change in syllabic structure is not challenging enough to interfere. Moreover, rule learning over ABB patterns in syllables has been found as early as in the neonatal brain (Gervain et al., 2008). Therefore, if this mechanism is automatic for identity-relation grammars we may need a more complex input to generate an interference. Additionally, in this study, participants passively listened to the stream of sounds. The level of attention is important and can create an interference in the generalization of non-adjacent structures, but, interestingly enough, not in the generalization of adjacent repetitions implemented over syllables or vowels (Toro, Sinnett, et al., 2011). To generate an interference, we could use, for instance, abstract rules following an AXC pattern, where A and C have a non-adjacent dependency and X is a variable that takes different values. Or we could use syllabic structure to carry the abstract rules, that is, use CV-CVC-CVC words that follow an ABB rule, or CVC CV CVC words that follow an ABA rule.

### 2.6.4 On Statistical learning

In an ERP/MEG study, Teinonen and Huotilainen (2012), found that the N1 and N400 components were modulated at the single syllable level, and reflected statistical segmentation of a stream of nonsense syllables into words by the use of transitional probabilities. The same authors had previously demonstrated that neonates used transitional probabilities between syllables to successfully segment a syllabic stream into words (Teinonen et al., 2009). Newborns responded differently to initial syllables than to final syllables, suggesting that these syllables were the key to word boundaries. Moreover, the negative deflection they found in initial syllables was very similar to the one found in adult participants in other studies of speech segmentation. These results, suggest that since we are born we can track syllables and distinguish between them by computing probabilities of co-occurrence that lead to word-like units. In our study, participants could successfully segment the stream in its nonsense words and they could even adopt as words the tp-words (modified syllabic structure words), but at the same time, they could perfectly distinguish between words and tp-words.

Tp-words were modified versions of the word, they had an initial syllable that had a new consonant inserted in between the CV syllable, and the last syllable was intact (e.g. word was *ca-ri-mu*, while tp-word was *cra-i-mu*). It is possible that since the change in the initial syllable was seen as not very abrupt, and the last syllable was intact, that it was easily generalized by participants. That is, we left critical information that participants used to adopt tp-words as words. From the CV hypothesis (Nespor et al., 2003), we know that consonants and vowels carry different functional roles in language acquisition. In particular, consonants are preferentially used to segment the stream into words and recognize these words. Our data is congruent with the finding that infants and adults use the initial and final syllable to parse the stream, and the main use of consonants, or at least, the first consonant, to this end. It is likely that the middle syllable, formed only by a vowel, did not provide useful information, as it happens in grammar learning experiments, where edge-position syllables are preferentially used to extract regularities (Endress et al., 2009). But this hypothesis would require further research and a more technical approach, such as the use of ERPs, to be replicated and confirmed.

### 2.6.5 The importance of the syllable

The syllable has a privileged status in language. Räsänen et al. (2018) found that, regardless of the language's rhythmic class, it was possible to parse the stream in syllable-like chunks with no need to use a linguistic-specific mechanism, suggesting that syllable-like units were used in language acquisition by pre-linguistic infants. The natural oscillations in the human brain are entrained to timescales that coincide with the phonemic and the syllabic segments in the speech stream (e.g. Giraud et al., 2007; Giraud & Poeppel, 2012; Morillon et al., 2010). Even though we could not find in the mechanisms that we tested any interference with syllabic structure, we believe that we have opened a door to a better understanding of how statistical learning and rule learning operate and interact with the basic processing unit of language, that is, the syllable.

## 2.7 Conclusions

In this chapter, we explored in a passive listening behavioural paradigm, if a change in syllabic structure could interfere with two mechanisms that are critical for language acquisition: rule learning and statistical learning.

*Syllabic Structure Interference in RL and SL*

In the rule learning experiments, results show that learning and generalizing a repetition-based grammar over syllables and over vowels is not interfered by a syllabic structure change. Additionally, results suggest that extracting abstract rules over syllables is easier than extracting abstract rules over vowels. The latter results suggest two things: (1) that they are congruent with an automatic perceptual mechanism sensitive to adjacent repetitions that would consider the relationship between vowels in ABB words as non-adjacent segments, and (2) that abstract rule learning over syllables is not dependent on its constituent elements, such as vowels, but is performed regarding the syllable as a unit.

In the statistical learning experiments, syllabic structure did not interfere in the segmentation and recognition of words presented in the continuous stream. Participants could readily discriminate words presented in the familiarization phase with the same words under a syllabic structure modification. Evidence seems to be congruent with other studies showing that word segmentation and word learning is based on edge syllables within a word.

# Chapter 3

# ERP Signatures in an Auditory Rule Learning Paradigm with Syllabic Structure Interference

In the previous section, we provided behavioural evidence that syllabic structure did not interfere in the learning of a rule over syllabic and vocalic instances. In this section, we want to explore the electrophysiological responses triggered by the presence of an unexpected syllabic structure change during the generalization of an abstract rule.

## 3.1 Introduction

Rule learning has been claimed to be one of the stepping-stones of language learning. In fact, it has been claimed that the mechanism responsible for detecting and generalizing abstract rules is fundamental to acquire the syntactic rules of a language (see Marcus, Vijayan, Bandi Rao, & Vishton, 1999). One of the best ways to study rule learning is over artificial grammars. They allow the researcher to carefully control the grammar's complexity, and to understand and infer effects from the results. The simplest artificial rule learning experiments are created with repetition-based grammars. These grammars consist of a repetition that can be adjacent, such that there is an immediate repetition of the same variable (ABB, as in ***coco***_nut_), or non-adjacent, such that the repetition happens within a distance (ABA, as in ***bo***_no_***bo***). In the two previous examples, the variable to which we applied the repetition was the syllable, but it could also have been the vowel (e.g. _T_***o***_led_***o)*** or the consonant (e.g. ***mim***_osa)_. Importantly, the discovery of such abstract patterns seems to be very reliable from the moment of birth, as research has shown that newborns are able to learn ABB, but not ABA rules, over syllables (Gervain et al., 2008). The authors argued that there is an automatic perceptual mechanism sensitive to adjacent repetitions present in the newborn brain.

Endress, Nespor, and Mehler (2009) proposed that specialized mechanisms, or 'perceptual or memory primitives' (POMPs), constrain the learnability of rules and statistical computations in language. One of the POMPs is sensitive to identity relations, and the other is sensitive to edge positions and uses them to extract regularities. So, perceptual systems (including language) would generate a biased interpretation of the world from the sensory input they receive. Endress and Hauser (2009) found that participants were not able to learn adjacent repetitions over syntactic categories (e.g. nouns and verbs) if their combination was syntactically impossible (noun-noun-verb or verb-verb-noun). Even when the authors asked participants to explicitly look for the abstract rule, they still failed. This suggested that humans have a sort of "pattern deafness". Such *deafness* would result from the syntactic system trying to make participants search for interpretations (over verbs and nouns) that accommodate to correct syntactic principles. Such interpretations would make them fail to detect the abstract regularities. This is a very relevant example of how linguistic structures can strongly influence the detection of very simple abstract patterns. Another example of linguistic structures modulating how abstract rules are learned comes from functional differences between consonants and vowels. Research has shown that vowels and consonants play different roles during language processing and, while vowels are excellent candidates for rule learning, consonants show an advantage at parsing the stream and at helping memorize words (Hochmann et al., 2011; Nespor et al., 2003; Toro, Nespor, et al., 2008). Thus, functional differences among phonemes determine whether consonants and vowels are better targets for statistical or rule extracting mechanisms. However, to the best of our knowledge, little is known about whether the basic linguistic processing unit, (that is, the syllable) might modulate the learnability of these structures.

The syllable is an important unit in language. Our brain synchronizes to the rhythm of linguistic structures, such as the syllable or the phonemes. That is, speech is parsed and processed simultaneously at multiple temporal levels that follow the hierarchical organization (syntax) of speech, such as the level of the sentence, the word and the syllable (Giraud et al., 2007; Hickok & Poeppel, 2007). Syllables, therefore, play an important role, not only to segment the stream (J. Mehler, 1981; Segui et al., 1981), but to readily obtain information from the stream. In Chapter 2, we showed that it was easier to extract regularities from syllables than from vowels. Thus, we already noticed that the syllabic level is of great important in speech processing, and has also been proven to be of importance in speech production (Giraud et al., 2007).

In the auditory cortex, neural activity is modulated by the frequencies that coincide with the rhythms in speech. Moreover, the onset of speech resets neural oscillations so that they perfectly align with speech rhythms (of phonemes and syllables). Thus, speech segmentation relies on the hierarchical coupling between delta, theta and gamma oscillations within the auditory cortex, that correspond to boundaries in speech elements (Gross et al., 2013). Importantly, there is a hierarchical coupling of brain oscillations between frequency bands, so that, for instance, theta phase modulates gamma amplitude. This might suggest that the syllable level of processing modulates lower hierarchical levels such as phonemes. Such modulation has been shown to be stronger for intelligible than unintelligible speech (Gross et al., 2013).

Studies of ERPs on syllables have shown the triggering of a mismatch negativity (MMN) response reflecting syllabic discrimination. The MMN, elicited around 100-250 ms after stimulus onset, is a negative deflection product of the perceptual mismatch elicited after an infrequent stimulus is presented interspersed in a stream of frequent stimuli (that share some rule or physical characteristics). It has been shown that the MMN can be triggered as a response to the discrimination of linguistic stimuli, such as consonant-vowel (CV) syllables or phonemes. Interestingly, only participants that discriminate behaviourally the syllables or phonemes elicit a MMN (Näätänen, 2002). Monte-Ordoño and Toro (2017a) presented participants with an auditory oddball paradigm that could either present standard nonsense words that followed an ABB rule on vocalic segments (Vowel condition, such as *fufeke*) or over consonant segments (Consonant condition, such as *fukuku*). Such standard words were sporadically interrupted by a deviant word that had new phonemes (phoneme deviants), or a deviant word that had new phonemes and followed a different abstract rule (rule deviants). Results showed that a P1/MMN was elicited at around 50 ms and 150 ms at the vowel and the consonant condition and after both type of deviants. The authors interpreted the presence of these early perceptual components as responding to the mismatch elicited by the deviants' novel phonemes. Interestingly, the amplitude of the MMN was larger in the consonant than in the vowel condition, congruent with the abovementioned differences in functional roles that consonants and vowels play in speech processing (where consonants have more weight in word recognition, see Nespor et al., 2003).

Other studies have shown the presence of a P300-like component after rule violations. For instance, in Monte-Ordoño and Toro (2017b), they conducted an auditory oddball paradigm recording event-related potentials (ERPs). In their study, participants were presented with trisyllabic CVCVCV nonsense words. Standards followed an ABB rule over syllables (presented 80% stream). They presented two types of deviants, a phoneme deviant that differed only in phonemes from standards (presented 10%), and rule deviants, that differed from standards in their phonemes and their rule (they followed an ABA rule over syllables, presented 10%). Results showed a P300-like component after rule violations that positively correlated with the performance scores of participants. This component has been found in other studies were there was a violation of a morphosyntactic rule (Havas et al., 2017), or a rule violation of a vowel harmony (Mclaughlin et al., 2010).

In the present study, we aim to explore the neural responses triggered by changes in syllabic structure during rule learning. Thus, we will study the role that syllabic structure plays during the extraction of repetition-based grammars with adjacent (Experiment

1) and non-adjacent (Experiment 2) repetitions over syllables. To this effect, we tested participants in a three-stimuli auditory oddball paradigm, with standard trisyllabic consonant-vowel (CV) nonsense words (present 80% of the stream) and two deviants: Syllabic deviants, created with different phonemes, different syllabic structure (CVC), and same rule than standards (10%), and Rule deviants, created with different phonemes, different syllabic structure (CVC), and different rule than standards (10%). We recorded the participants' event-related potentials (ERP) during the experiment. Participants were told to ignore the auditory nonsense sounds and asked to attend a silent film. A test to assess behavioural rule learning and some questions about the distractor film were asked at the end of the experiment. We hypothesized that at the first syllable we would observe a mismatch negativity (MMN) corresponding to the syllabic structure change, and at the onset of the third syllable we would observe a P300-like component from the difference between deviants elicited by a rule violation.

## 3.2 Experiment 1

In this experiment, participants were tested with nonsense words following an abstract ABB pattern implemented over syllables. Standard words were formed by CVCVCV nonsense words following an ABB rule. Syllabic and Rule deviants were formed by CVCCVCCVC nonsense words with new phonemes. Syllabic deviants followed an ABB pattern (just as the Standards), while Rule deviants followed a diversity-based pattern (ABC, first two syllables were the same as in Syllabic deviants, the last syllable differed).

### 3.2.1 Methods

#### *Participants*

Twenty-one native Spanish speakers (11 female; age: M=22.29, SD=2.22) from the Neuroscience Laboratory database of the Center for Brain and Cognition at the Pompeu Fabra University participated in the experiment. All participants were right-handed (based on the Edinburgh Handedness Inventory; Oldfield, 1971), reported normal hearing and had no history of neurological disorders. Participants gave written informed consent prior to the experiment and were compensated for their participation.

#### *Familiarization stimuli*

Familiarization stimuli consisted in highly frequent standard nonsense words and infrequent deviant nonsense words. Forty-five trisyllabic CVCVCV nonsense words were used as standards (see all stimuli in Annex 1,Table 1). Phonemes used to create syllables were /f/, /b/, /m/, /d/, /t/, /e/, /i/, /o/. Fifteen syllables were used to create the trisyllabic words: *fe, fi, fo, be, bi, bo, me, mi, mo, de, di, do, te, ti* and *to*. Words followed an ABB rule (meaning that the second and third syllables were the same; as in f*ebobo* or *midede*).

A hundred forty-four trisyllabic CVCCVCCVC nonsense words were used as deviant stimuli. Deviants differed from standards in their phonemes and in their syllabic structure. Phonemes used to create deviants were /p/, /n/, /r/, /l/, /c/, /g/, /a/, /u/. All syllables in deviant stimuli had a CVC structure, resulting in thirty syllables (*pan, pun, par, pur, pal, pur, can, cun, car, cur, cal, cul, gan, gur, gal, gul, lan, lun, lar, lur, nal, nul, nar, nur, ral, rul, ran and run*). Two types of deviants were created: 72 Syllabic deviants and 72 Rule deviants. Syllabic deviants followed an ABB pattern on the syllables (just as standard stimuli; e.g., *parcuncun* or *nulgargar*) and differed from standards in their syllabic structure (CV and CVC). Rule deviants followed an ABC pattern (e.g. *parcungal* or *nulgarpun*). Syllabic and Rule deviants only differed in the third syllable. Their first and second syllables were exactly the same. A female native Spanish speaker produced CV (consonant-vowel) and CVC (consonant-vowel-consonant) syllables used as stimuli. When recorded, target syllables were preceded by a stressed syllable to ensure a neutral intonation. Syllables were normalized using Praat (www.praat.org). Pitch was set to 215 Hz, and the intensity was set to 75 dB. Duration for CV syllables was set to 340 ms and for CVC syllables to 390 ms.

### *Behavioural test stimuli*

New nonsense words were created for the behavioural test. All syllables in the test words had a CVC syllabic structure (see Annex 2, Table 14. Words presented at the behavioural test. Rule words and Non-Rule words differed only in the third syllable. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the syllables.). Phonemes used to create these stimuli were /m/, /s/, /l/, /r/, /a/, /e/ and /o/. Thirty-six syllables were created from these phonemes: *lam, lar, las, lem, ler, les, lom, lor, los, mal, mar, mas, mel, mer, mes, mol, mor, mos, ral, ram, ras, rel, rem, res, rol, rom, ros, sal, sam, sar, sel, sem, ser, sol, som and sor*. Two types of test words were created. There were 16 rule words that followed an ABB pattern on the syllables (e.g. *ramlesles* or *somrelrel*), and 16 non-rule words that followed an ABC pattern on the syllables (e.g. *semlormal* or *lersamrol*). Behavioural test stimuli were recorded using the same procedure as in the familiarization stimuli. It consisted of CVC syllables normalized to a mean duration of 432 ms (SD=.037), a pitch of 215 Hz and an intensity of 75 dB.

### *Experimental procedure*

All participants were tested in a sound-attenuated room. They sat comfortably in an armchair in front of a screen. Sound stimuli were presented through speakers. Participants were asked to pay attention to a silent film and ignore the sounds. They were told that at the end of the experiment they would have a test to make sure they were attentive to the film. We used an oddball paradigm to present the nonsense words. The experiment consisted of two blocks of 20 min each, with a 2-min pause between the blocks. Each block consisted in the presentation of 639 words: 495 standard words, 72 syllabic deviants, and 72 rule deviants. Standard stimuli were randomly repeated 11 times. Deviant stimuli were randomly presented every 3 to 7 standard words. Inter-stimulus interval (ISI) was set to 800 ms. The probability of syllabic and rule deviant presentation was 0.11. Presentation of stimuli was pseudorandomized within blocks. Each block for each participant had a different randomization.

After the presentation of the two blocks, there was a behavioural test in the form of a two-alternative forced-choice (AFC) test. The test had sixteen questions. Each question consisted of the presentation of a rule word and a non-rule. ISI was set to 750 ms. The order of presentation of rule and non-rule words was counterbalanced. After the behavioural test, participants answered some questions about the silent film.

### *ERP recording and data analysis*

We used a 32-channel actiCAP (Brain Products GmbH, Germany) to record the EEG signal at a sampling frequency of 500 Hz, using the modified combinatorial nomenclature (MCN). Twenty-eight electrodes were recorded from the scalp (Fp1, 2; F3, 4, 7, 8; Fz;

FC1, 2, 5, 6; C3, 4; Cz; T7, 8; CP1, 2, 5, 6; CPz; TP9, 10; P3, 4, 7, 8; Pz; Oz). Additionally, one electrode was placed at the left mastoid (MSDL), one at the right mastoid (MSDR), and two electrodes were placed on the right eye to control for eye movements (one at the outer canthi (Heog) and one below the eye (Veog)). An electrode placed on the tip of the nose was used as the online reference. Offline, the data were re-referenced to the average of the left and right mastoid. Electrode impedances were kept under 5 kΩ. EEG pre-processing and analysis was carried out using the FieldTrip toolbox in Matlab (Oostenveld, Fries, Maris, & Schoffelen, 2011).

ERP data were divided into two trials corresponding to the first and the second block of the experiment. An off-line low-pass filter at 0.5 Hz and a high-pass filter at 50 Hz was applied. Eye movement, muscular noise, and heartbeat were removed by performing an independent component analysis (ICA). Trials were re-defined into three sets: Syllable 1, that started at the onset of the word, Syllable 2, that started at the onset of the second syllable, and Syllable 3, that started at the onset of the third syllable. Epochs of 900 ms were created for each Condition (Standard, Syllabic deviant, and Rule deviant) and at each Syllable (1, 2 and 3). Epochs started 100 ms prior to the stimulus onset to use the -100 to 0 ms window for baseline correction. However, at the first syllable, when analysing standard vs the two types of deviants, we analysed only until 340 ms after the onset of the syllable, since any significant difference after 340 ms could be due to the difference in duration between both stimuli and the onset of the next syllable. Trials were rejected if they exceeded ±75 μV. A minimum of 80% of accepted trials was the threshold to include a participant in the analysis. The average percentage of trials accepted per subject was 99.41% for Standard trials, 99.52% for Syllabic deviant trials, and 99.38% for Rule deviant trials.

Since we acquired data that requires a multi-sensor analysis approach, and we needed to account for the multiple comparisons problem, we used a cluster-based permutation test to evaluate our non-averaged ERP data (a detailed account of the steps for this test can be seen in Maris & Oostenveld, 2007). We conducted a series of cluster-based permutation tests at each syllable. In Syllable 1, we compared standards and the two types of deviants (we merged the two deviants as they were exactly the same in the first syllable). In Syllable 3, we performed the comparison of Standard vs Syllabic deviants, Standard vs Rule deviants, and Syllabic deviants vs Rule deviants. Additionally, we compared Syllabic deviants vs Rule deviants in Syllable 1 and 2 to corroborate that our stimuli was perceived as equivalent for the first two syllables. The electrodes included in the analysis were: FC1, FC2, F3, F4, FC5, FC6, Fz, C3, C4, Cz, CP1, CP2, CP5, CP6, P3, P4, P7, P8, Pz, Oz. We report the significant time windows and their cluster-level p-value.

To further explore the effects and interactions between blocks and regions at each condition and syllable, we performed repeated-measures ANOVAs. We obtained the time windows for the ANOVAs from the cluster-based permutation tests. The ANOVAs have as within-subjects factors Block (Block 1, Block 2), AP (Anterior, Posterior), and Position (Left, Central, Right). We thus obtained 6 regions in the scalp: anterior-left (AL, electrodes F3, FC1, FC5, C3), anterior-central (AC, electrodes Fz, FC1, FC2, Cz), anterior-right (AR, electrodes F4, FC2, FC6, C4), posterior-left (PL, electrodes CP1, CP5, P7, P3), posterior-central (PC; electrodes Pz, Oz, P3, P4) and posterior-right (PR, electrodes CP2, CP6, P4, P8). The electrodes included in the analysis were the same as in the cluster-based permutation tests. For the analyses we used the peak voltages of the difference waves. We averaged them over the electrodes in each region. We used the Huynh-Feldt epsilon when there was a violation of sphericity, and the Bonferroni correction for multiple comparisons when it applied. Only corrected p-values are reported.

### 3.2.2 Results

#### *Behavioural results*

We calculated the performance in the behavioural test as the percentage of correct responses to the sixteen 2-AFC answers from each participant. A one-sample t-test was performed to assess if the performance of the participants was above chance level (50%). The results showed that participants could generalize the rule above what it is expected from chance (M=74.69, SD=16.53; t(19)=6.68, p<.001). That is, participants learned the ABB rule implemented by the standard words and generalized it to novel words with different syllabic structures.

#### *ERP results*

##### Syllable 1

The comparison between Standard and Deviants (both Syllabic and Rule deviants merged together) yielded a significant negativity from 120 to 166 ms (cluster p=.010) that was followed by a negativity from 218 to 314 ms (cluster p=.002). As expected, the comparison between Syllabic deviants and Rule deviants showed that there were no significant differences between them (see Figure 6).

In order to examine the differences observed in the comparison between Standard and Deviants across blocks and regions in the scalp, we conducted a repeated-measures ANOVA at each time window with the within-subjects factors Block (Block 1, Block 2), AP (Anterior, Posterior) and Position (Left, Central, Right). At the early time window, from 120 to 166 ms (congruent with an N1, see Figure 5), we observed a main effect of AP (F(1,19)=34.78, p<.001). The interactions AP x Position (F(2,38)=9.42, p<.001) and Block x AP x Position (F(2,38)=4.82, p=.014) were also significant.

Pairwise comparisons revealed that at both blocks, the AC region was significantly more involved in the response (AC and AL, p<.001; AC and AR, p=.004). At the time window from 218 to 314 ms (congruent with a MMN, see Figure 5), we found a main effect of AP (F(1,19)=61.27, p<.001) and Position (F(2,38)=6.06, p=.017) and a significant AP x Position interaction (F(2,38)=13.09, p<.001). Pairwise comparisons demonstrated that the AC region had the largest amplitudes (AC and AL, p<.001; AL and AR, p<.001).

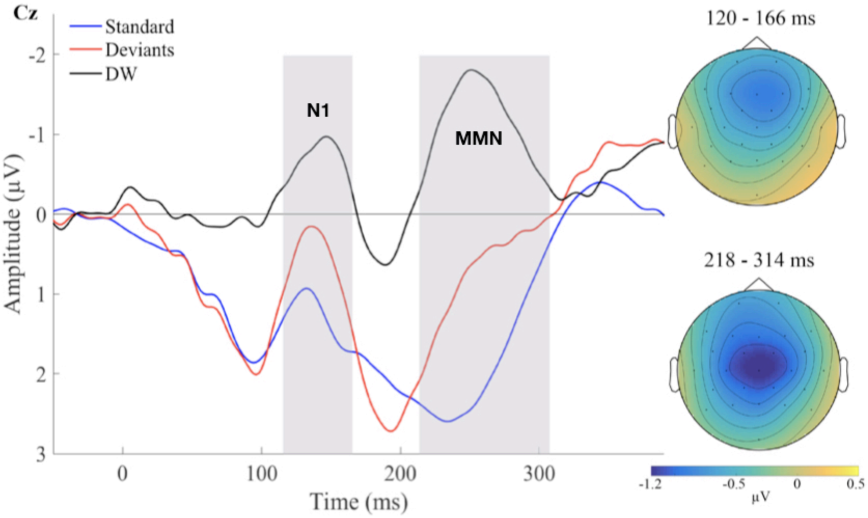

**Figure 5.** Syllable 1, Standard vs Deviants. On the left, grand average of standards (blue), deviants (red), and their difference wave (black) in the Cz electrode. Shadowed areas depict significant time windows. On the right, topographical plots of the difference waves for the two significant time windows, N1 (top) and MMN (bottom).

### Syllable 2

We performed a comparison between Syllabic deviants and Rule deviants. As expected, we did not observe any significant differences between them (see Figure 6).

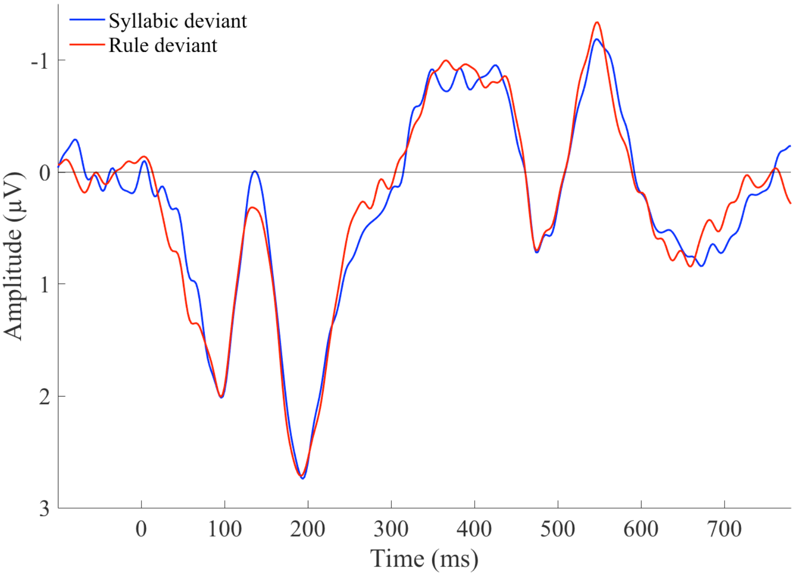

**Figure 6**. Grand average of Syllabic deviant and Rule deviant from the onset of the first syllable until the end of the second syllable. No significant differences were found between the deviant stimuli. Plot represents data from electrode Cz.

### Syllable 3

The comparison between Standard and Syllabic deviants yielded a significant negativity from 360 to 464 ms (cluster p=.010). The comparison between Standard and Rule deviants yielded a large positivity from 52 to 356 ms (cluster p=.002). Results from the comparison between Syllabic deviants and Rule deviants showed a large positivity from 134 to 520 ms (cluster p=.002).

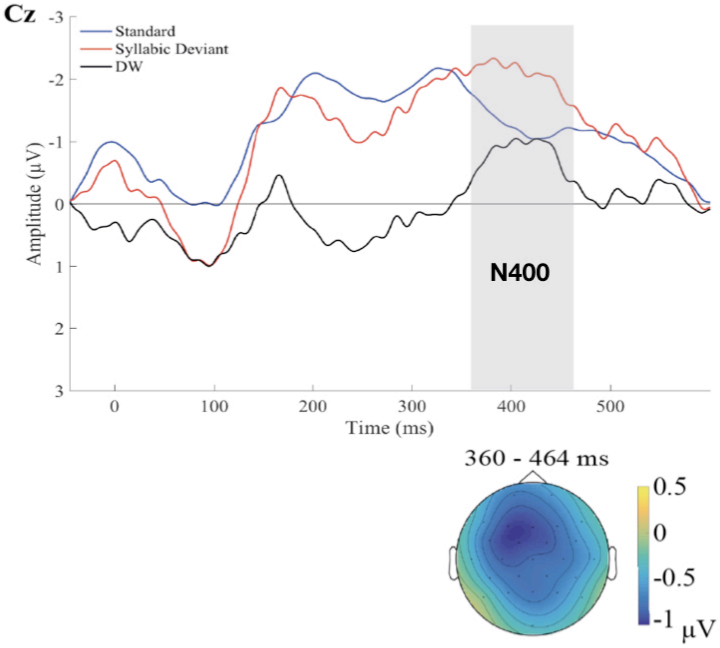

**Figure 7.** Grand average plot of the standards (blue), the syllabic deviants (red) and their difference wave (black) in the Cz electrode. The shadowed area corresponds to the significant time window N400. Below, the topographical plot of the difference wave (in amplitude) of the N400. Its corresponding topographical map is below.

We conducted Block x AP x Position repeated-measures ANOVAs at each of the significant time windows. Results from the comparison at the time window between 360 and 464 ms (N400, see Figure 7a) yielded a main effect of AP (F(1,19)=14.14, p=.001) and Position (F(2,38)=6.50, p=.008), showing that the negativity was significantly larger over anterior regions than over posterior regions and over central than over left (p=.022) or right regions (p=.001). The analysis of the differences observed at the time window between 52 and 356 ms (split into two windows: 52-125 ms is congruent with a P1, and a large Positivity, 160-356 ms, see Figure 7b) yielded a main effect of AP (F(1,19)=66.58, p<.001), and the interaction AP x Position (F(2,38)=14.07, p<.001). Thus, the positivity was larger in AC electrodes (pairwise comparisons: AC and AL, p<.001; AC and AR, p<.001). Finally, the comparison at the time window between 134 and 520 ms (congruent with a P300-like component, see Figure 9) yielded a main effect of AP (F(1,19)=68.87, p<.001), and the interaction AP x Position (F(2,38)=7.84, p=.002). These results show that the peak amplitudes were located in the anterior region, specifically in the AC region (pairwise comparisons: AC and AL, p<.001; AC and AR, p=.001).

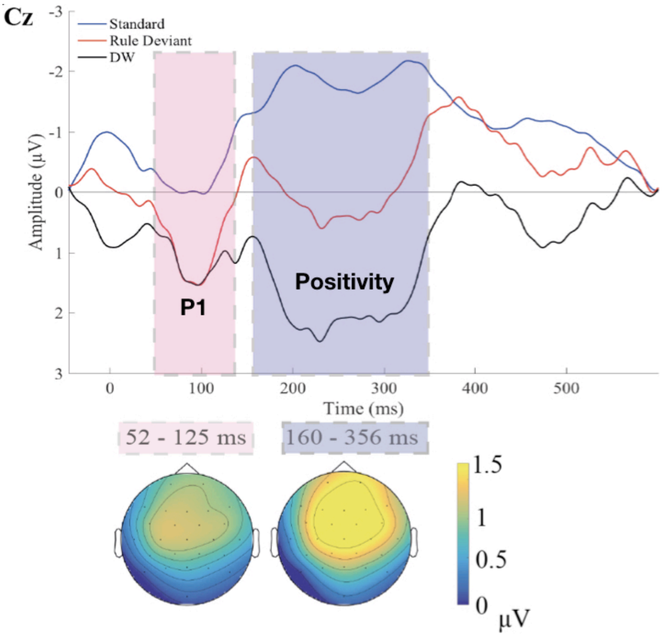

**Figure 8.** Grand average plot of the standard (blue), the rule deviants (red) and their difference wave (black) in the Cz electrode. The total shadowed area corresponds to the significant time window from 52 to 356 ms. We divided the time window in two: in pink, the P1 from 52 to 125 ms, and in purple, the Positivity from 160 to 356 ms. Their corresponding topographical maps are below.

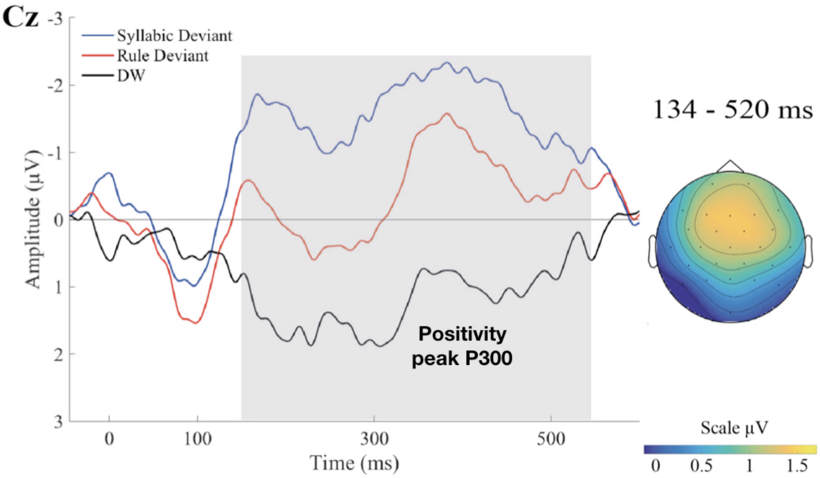

**Figure 9.** Grand average of the syllabic deviants (blue), the rule deviants (red) and their difference wave (black). The shadowed area corresponds to the significant time window from 134 to 520 ms. On the right, the topographical plot of the difference wave during the significant time window. This positivity had its peak voltage around 300 ms, that is why we considered it a P300-like component.

### 3.2.3 Discussion

In this study, we wanted to explore the influence of a change in syllabic structure over the generalization of a repetition-based abstract rule (an ABB rule) embedded in syllables. The behavioural test showed that participants easily generalized the rule. The ERPs showed that an N1/MMN emerged after responses to deviants at the onset of the first syllable. At the onset of the third syllable, an N400-like component was elicited after tokens with new phonemes and syllabic structure that followed the rule instantiated by standards (Syllabic deviants). Also, at the onset of the third syllable, a large positivity composed of a P1 and a P200-P300 deflection, was elicited after Rule deviants. Finally, a P300-like component was elicited after the violation of the rule followed by standards. This component was found by comparing Syllabic and Rule deviants, since the only difference between them is the abstract rule they are following.

Differences elicited during the first syllable at the N1 time window, indicate that participants detected a change in the features of the sound between standard and deviant stimuli. This most likely corresponds to the fact that the phonemes conforming standards and deviants were different. The N1 is an “obligatory” component that is controlled by the spectro-temporal features of sounds (Näätänen & Picton, 1987). It is called obligatory because it is the signature that the auditory cortex has detected the sound stimulus. This component appears together with other components in the P1-N1-P2 complex, all components related to sound detection (Alain & Tremblay, 2007; Näätänen, 1990). The more prominent the difference between sound features, the larger the amplitude of the N1 (Escera, Alho, Schröger, & Winkler, 2000). In our study, deviant sounds were quite different from the standards: they had new phonemes, and new syllabic structure, which lead to different phoneme duration (vowels were shorter in deviant CVC syllables, compared to standard CV syllables, since they were followed by a consonant). These differences might have elicited a large N1 component.

The later component that we found after the presentation of the first syllable is the MMN. This component is obtained by subtracting the deviant to the standard wave, and is elicited when there is a mismatch between the actual auditory input (the deviant) and the information encoded in memory (the standards; Näätänen, Kujala, & Winkler, 2011). The MMN can be elicited by acoustic features or more abstract relations, e.g. rules. Its latency and amplitude depends on how different the deviant is to the standard. In our case, the MMN is consistent with the detection of a change in syllabic structure from CV to CVC. In fact, similar studies, that do not involve changes in syllabic structure from standard to deviants, do not find a MMN after the presentation of the first syllable in deviant words (see Monte-Ordoño & Toro, 2017b). We analysed the data from that study for comparison purposes, as the analysis for the responses after the first syllable were not included. We did not find any significant differences between standards and the two types of deviants after the presentation of the first syllable (see Annex 3, Figure 15 and Figure 16) in the data from Monte-Ordoño & Toro (2017b). Therefore, it seems plausible to assume that the MMN that we find in the present experiment is due to the change in syllabic structure.

The N400-like negativity found at the third syllable had an anterior-central distribution. The N400 component has been related to semantic processing and lower levels of lexical processing such as lexical access (Kutas & Federmeier, 2011; Lau, Phillips, & Poeppel, 2008). Originally, the N400 was found over centro-parietal electrodes and signaling word semantic incongruences in sentences as in "I spread the warm bread with *socks*" (Kutas & Hillyard, 1980). Later on, this component has been elicited in other linguistic contexts (orthographically legal nonwords, Mclaughlin et al., 2010; indexing on-line word segmentation, Cunillera, Toro, Sebastián-Gallés, & Rodríguez-Fornells, 2006; or in the lexicality and the semantic priming effect, Chwilla, Brown, & Hagoort, 1995), but also in studies related to faces and pictures (Lau et al., 2008). Moreover, some studies have reported the emergence of this component over fronto-central scalp distributions (for instance, Cunillera, Toro, Sebastián-Gallés, & Rodríguez-Fornells, 2006; Monte-Ordoño & Toro, 2017; Sun, Hoshi-Shiba, Abla, & Okanoya, 2012). In our study, the N400-like negativity seems to be induced by the detection of a word-level incongruity led by a lexical process related to orthographic and phonological processes (see Deacon, Dynowska, Ritter, & Grose-Fifer, 2004). Our nonsense words lacked any semantic content and could not have been learned or memorized because they only appeared twice during the experiment. In one of the studies by Mclaughlin et al. (2010), native Finnish speakers, as well as English learners of Finnish (first year learners), elicited an N400 effect when they contrasted orthographically legal pseudowords with Finnish words. First year learners' brain responses showed discrimination between pseudowords and real words from the first session. However, the smaller N400 observed in learners, compared to natives, indicated that they did recognize a mismatch between pseudowords and words but their representation of the incongruence was not quite solid yet. In our study we also observed a small N400 effect after the presentation of Syllabic deviants. These deviants were created from orthographically legal syllables (such as *pun* or *nal*), that combined created illegal pseudowords (such as *punnalnal* or *nallurlur*), and therefore eliciting a word-level incongruity when compared to standards.

Regarding the P1 component we observed when comparing Standards and Rule deviants, it is important to highlight that this component is not easily detectable in the signal. Results have shown that it decreases or even disappears with age, and is related to the sensory encoding of the auditory stimulus and the level of arousal of the participants (Key, Dove, & Maguire, 2005; Sharma, Kraus, McGee, & Nicol, 1997). This deflection seems to indicate that the change of phonemes was salient and participants were engaging their attention to this novelty. We could also find this deflection in responses after Syllabic deviants, but we did not find any significant differences at this latency.

The P300-like component found when comparing Syllabic to Rule deviants is indicative of a rule violation (see also the large positivity observed at this time window when we compared Standards and Rule deviants). To clarify, by comparing both deviants we are ruling out the differences in syllabic structure, and any difference obtained here could only be due to the difference in the abstract rule. In other studies, the authors have found a P300-like component associated with rule violations in vowel harmony by native Finnish speakers (Mclaughlin et al., 2010), in morphological rules (Havas et al., 2017), and in ungrammatical sentences (Tabullo, Sevilla, Segura, Zanutto, & Wainselboim, 2013). In these studies, the P300-like positivity was typically followed by a P600 component. The P600 component is elicited by syntactic anomalies and is associated with further processing of syntax or as an index of syntactic integration difficulty (Tabullo et al., 2011). In the study by Monte-Ordoño & Toro (2017b), the authors only found a P300-like component and hypothesized that the lack of a P600 component could be due to the simplicity of the task. We used nonsense words with no semantic content and a simple grammatical rule. The only difference between our study and theirs is in the new syllabic structure implemented over deviant stimuli. Since, in Chapter 2, we did not find a significant difference in performance between a generalization of the rule with or without a change in syllabic structure (see Chapter 2, Figure 3, results between Experiment 1 and Experiment 4; no significant differences in performance), we can assume that Monte-Ordoño & Toro (2017b) and our study have comparable difficulty, and therefore, assume that in both studies the P600 did not appear because further processing was not necessary.

Additionally, the positivity we observe could be related to a P3a component, or novelty P3a. The P3a is induced by stimulus-driven shifts of attention even in unattended auditory stimuli. Its latency and amplitude are related to task-processing demands. An increase in memory load decreases the P3a's amplitude and increases its latency (Escera et al., 2000; Polich, 2007). In the present study, this component appears quite early and with a considerable amplitude, possibly indicating that the violation of the rule was easily detected by the listeners. This is in accordance with the behavioural test's results, where participants obtained an average of 75% in performance (see Annex 1, Table 15).

Thus, our results suggest that the change in syllabic structure did not interfere in learning the rule, since neither behavioural performance nor electrophysiological responses between deviants were affected negatively by the change from a CV to a CVC syllabic structure. If we would have *not* seen a significant electrophysiological component when we compared Syllabic and Rule deviants, or if we reported an at-chance performance in the behavioural tests, then we could have suspected of an interference of syllabic structure. Moreover, our results closely mirror those observed when there are no changes in syllabic structure (as in Monte-Ordoño & Toro, 2017b). In both studies a P300-like component is observed after rule violations. Thus, if an interference would have taken place, there would be differences between their findings and ours.

Taken together, our results show that (1) there is no evidence of an interference between a change in syllabic structure and the learnability of an ABB rule, (2) a late MMN suggested that participants readily detect the new syllabic structure, (3) deviants that conform to the same rule as standards, but violate its phonemes and syllabic structure, generate an N400-like negativity related to a word-level incongruity, and (4) the difference between deviants elicited a P300-like positivity signalling a rule violation. The early emergence of this latency, prolonged up to 500 ms, indicates that participants in the present study were orienting their attention towards the auditory deviant stimuli and could easily extract and generalize the rule over an adjacent repetition-based grammar.

## 3.3 Experiment 2

Results from Experiment 1 suggest that participants generalized the rule over syllables following an adjacent repetition-based grammar (ABB) over syllables, even in the presence of a completely new syllabic structure. Now, we want to explore if the same change in syllabic structure could affect the learnability of a non-adjacent repetitive grammar (ABA) over syllables. To tackle this issue, we presented a new group of participants with a novel set of nonsense words that followed an ABA pattern as standards in an oddball paradigm.

### 3.3.1 Methods

#### *Participants*

Twenty native Spanish speakers (13 females; age: M=23.20, SD=2.73) from the Neuroscience Laboratory database of the Center for Brain and Cognition at the Pompeu Fabra University were included in the experiment. Two participants were discarded due to technical problems. All participants were right-handed (based on the Edinburgh Handedness Inventory; Oldfield, 1971), reported normal hearing and had no history of neurological disorders. Participants gave written informed consent prior to the experiment and were compensated for their participation.

#### *Familiarization stimuli*

The familiarization stimuli that we used were formed by the same syllables as in Experiment 1. The only difference is that the forty-five trisyllabic CVCVCV nonsense words we created followed an ABA rule (meaning that the first and third syllables were the same; as in bofebo or demide).

As in Experiment 1, we created a hundred forty-four trisyllabic CVCCVCCVC nonsense words that were used as deviant stimuli. We used the same phonemes and syllables as in Experiment 1. Two types of deviants were created: 72 Syllabic deviants and 72 Rule deviants. Syllabic deviants followed an ABA pattern on the syllables (just as standard stimuli; e.g., parcunpar or nulgarnul). Rule deviants followed an ABC pattern (e.g. parcungal or nulgarpun). Syllabic and Rule deviants only differed in the third syllable. Their first and second syllables were exactly the same.

### *Behavioural test stimuli*

We used the same CVC syllables created for the behavioural test in Experiment 1. The only difference was that the 16 rule words followed an ABA pattern on the syllables (e.g. ramlesram or somrelsol), while we used the 16 non-rule words from Experiment 1.

### *ERP recording and data analysis*

The ERP recording and data analysis was the same as in Experiment 1.

The average percentage of trials accepted per subject was 98.06% for Standard trials, 98.00% for Syllabic deviant trials, and 98.22% for Rule deviant trials.

### *Experimental procedure*

We used the same experimental procedure as in Experiment 1.

## 3.3.2 Results

### *Behavioural results*

Participant's performance was assessed as the percentage of correct responses to the sixteen 2-AFC answers from each participant. We performed a one-sample t-test to evaluate if their performance was over chance (50%), and results show that participants could generalize the rule over syllables with an ABA pattern (M=65, SD=18.30; t(19)=3.67, p<.001). That is, participants generalized the ABA pattern implemented over CV syllables in the standard stimuli, to new tokens that followed an ABA pattern over CVC syllables.

### *ERP results*

#### Syllable 1

The comparison between standards and deviants (both Syllabic and Rule deviants) revealed a significant early positivity from 52 to 94 ms (cluster p=.032). It was followed by a positivity from 168 to 202 ms (cluster p=.046), and later a negativity from 216 to 292 ms (cluster p=.002). As expected, the comparison between Syllabic and Rule deviants revealed no significant differences (see Figure 11).

We calculated a series of Block (Block 1, Block 2) x AP (Anterior, Posterior) x Position (Left, Central, Right) repeated-measures ANOVA for each significant component of the first syllable (see Figure 10). The P1 component revealed no significant effect or interaction. At the P2 component, we observed a main effect of Position (F(2,38)=4.50, p=.020) revealing that the positivity was mainly located in central regions (central and right, p=.010). The analysis of the MMN component, revealed a main effect of Block (F(1,19)=5.14, p=.035), AP (F(1,19)=94.74, p<.001), Position (F(2,38)=9.01, p=.001), and an AP x Position interaction (F(2,38)=26.15, p<.001). Pairwise comparisons showed that the AC region had larger amplitudes than the AL (p<.001) and the AR region (p<.001).

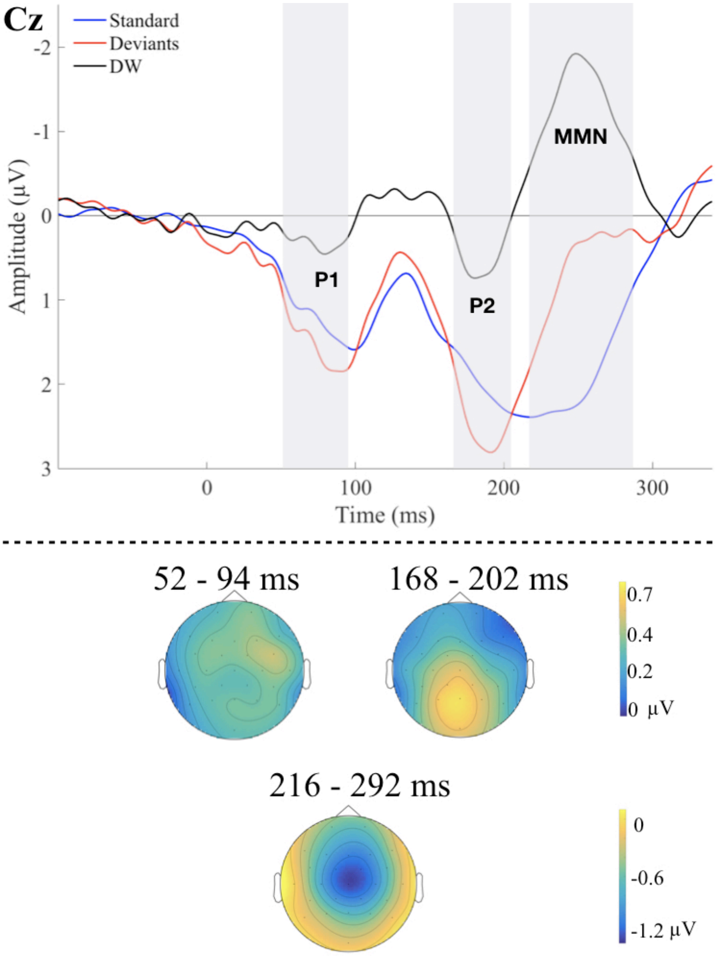

**Figure 10.** Results from Syllable 1, standards and deviants. Top: grand average of standards (blue), deviants (red) and their difference wave (DW, black). Shadowed areas correspond to significant time windows, namely P1, P2, and MMN. Bottom: topographical representation of the DW in the significant time windows P1 (top left), P2 (top right), and MMN (bottom).

### Syllable 2

The comparison between Syllabic and Rule deviants did not yield any significant differences between them (see Figure 11).

### Syllable 3

The comparison between Standard and Rule deviants yielded an early positivity from 54 to 142 ms (cluster p=.036) followed by a positivity from 174 to 356 ms (cluster p=.002). And the comparison between Syllabic and Rule deviants yielded a positivity from 256 to 320 ms (cluster p=.046). Importantly, the comparison between Standard and Syllabic deviants did not yield any significant differences between them.

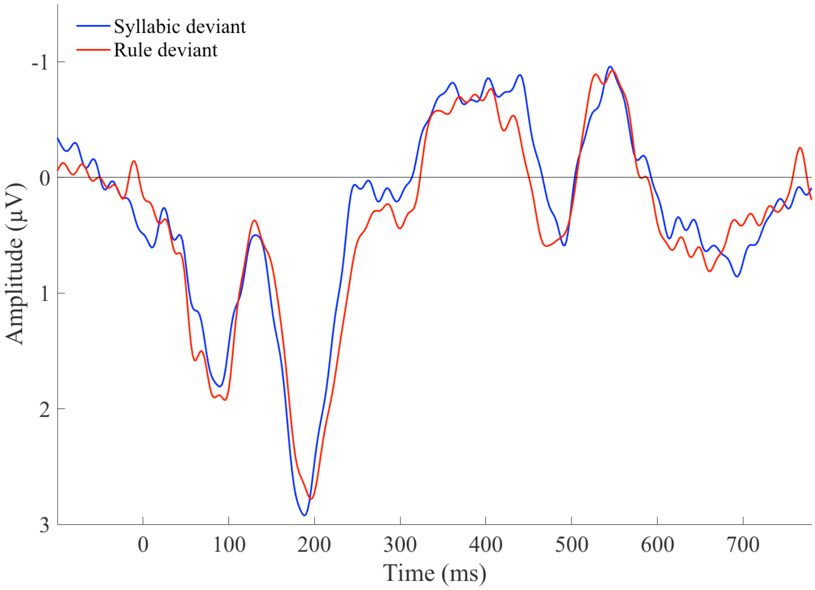

**Figure 11.** Grand average of Syllabic deviant and Rule deviant from the onset of the first syllable until the end of the second syllable. No significant differences were found between deviant stimuli. Plot represents data from electrode Cz.

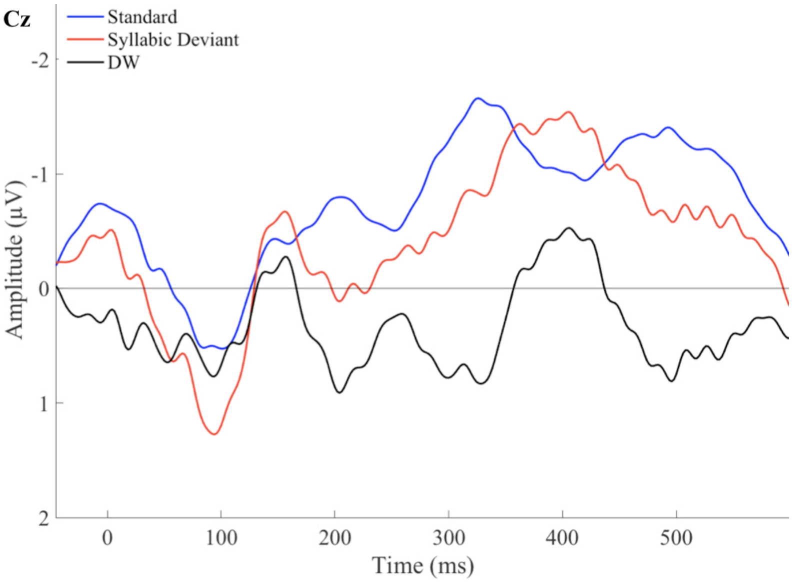

**Figure 12.** Results from Syllable 3, Standards and Syllabic deviants. Grand average of Standards (blue), Syllabic deviants (red) and their DW (black).

We conducted Block x AP x Position repeated-measures ANOVAs at each of the significant time windows. Results from the comparison between Standard and Rule deviants over the time window from 54 to 142 ms (P1, see Figure 13) revealed a main effect of AP (F(1,19)=14.93, p=.001), which indicated that the activity was located in the anterior regions. And results over the time window from 174 to 356 ms (P2 + P3, see Figure 13) showed a main effect of AP (F(1,19)=42.17, p<.001) and Position (F(2,38)=8.76, p=.001), and revealed significant interactions of

AP x Position (F(2,38)=5.24, p=.010) and Block x Position (F(2,38)=4.22, p=.029). Pairwise comparisons revealed that there were larger amplitudes in anterior regions, specially the AC region and, in Block 2, they were concentrated in central and right regions (AC and AL, p=.001; Block 2: C>L, p<.001, R>L, p=.002).

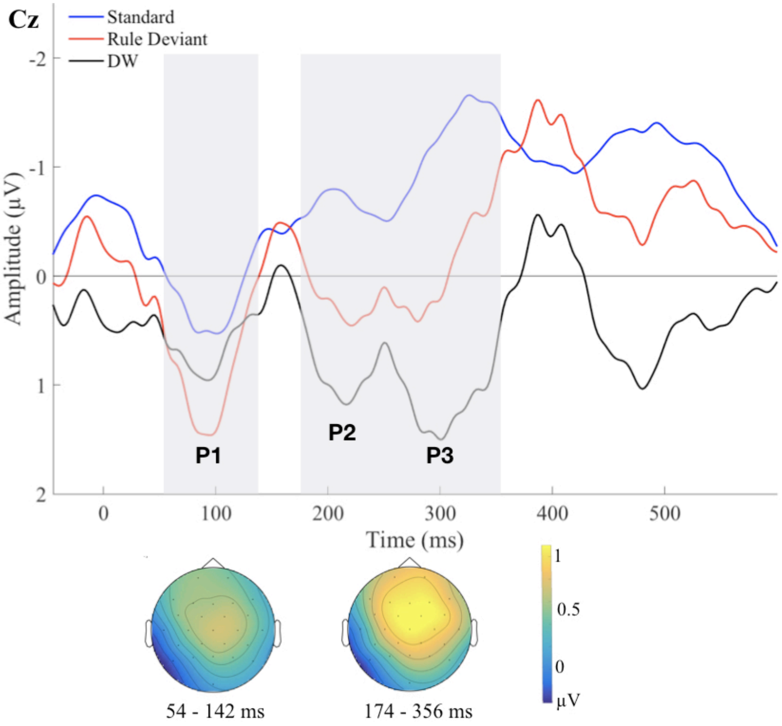

**Figure 13.** Results from Syllable 3, Standards and Rule deviants. Grand average of Standards (blue), Rule deviants (red) and their DW (black). Shadowed areas correspond to significant time windows, namely P1, and P2 + P3. Bottom: topographical representation of the DW in the significant time windows P1 (left) and P2 + P3 (right).

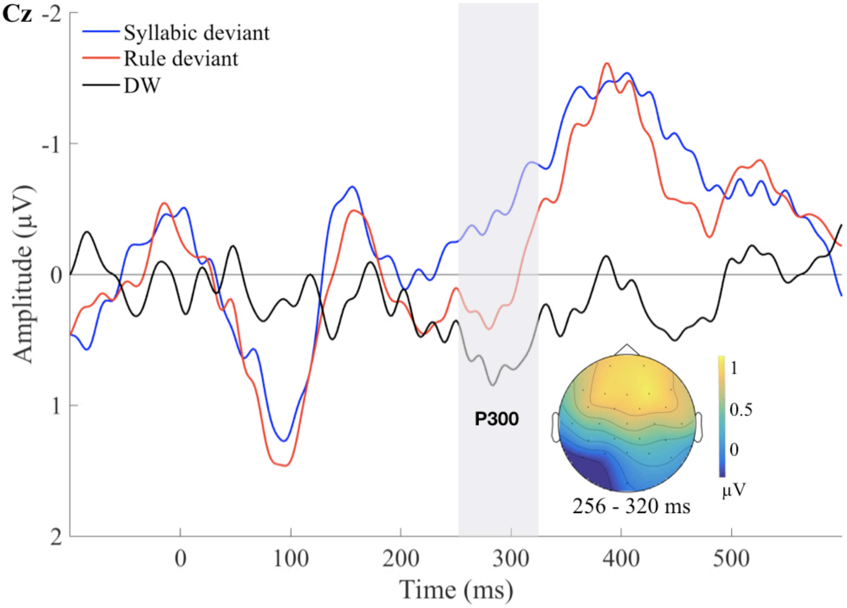

**Figure 14.** Results from Syllable 3, Syllabic and Rule deviants. Grand average of Syllabic deviants (blue), Rule deviants (red) and their DW (black). Shadowed area corresponds to the P300 significant time window, and on its right, the topographical representation of its DW.

The comparison between Syllabic deviants and Rule deviants, conducted at the time window from 256 to 320 ms (P300, see Figure 14), showed a main effect of AP (F(1,19)=19.55, p<.001) and Position (F(2,38)=4.29, p=.025), and revealed as significant the interactions Block x AP (F(1,19)=11.18, p=.003) and AP x Position (F(2,38)=3.89, p=.029). Pairwise comparisons showed that the AC region had significantly more activity than the AL region (p=.004). In Block 1, frontal electrodes had significantly more activity than posterior electrodes (p<.001).

### 3.3.3 Discussion

In this experiment, we explored the influence of a change in syllabic structure over the generalization of a non-adjacent repetitive rule over syllables. The behavioural test showed that participants could generalize the rule over differences in syllabic structure. In the ERPs, at the first syllable, we found a P1/P2/MMN elicited after responses to deviants, likely emerging from the detection of the new phonemes and the new syllabic structure compared to standards. A P1, and P2-P3 components were elicited after the third syllable in deviants that followed an incongruent rule (Rule deviants). Thus, these components are elicited by stimuli involving changes in phonemes, syllabic structure and grammatical rule. Finally, a P300-like component emerged comparing responses between deviants (Syllabic and Rule deviants). Because these deviants only differed in their underlying rule, such positivity was thus likely elicited by a rule violation.

The P1 component, elicited at the first and third syllable, is indicative of the arousal level of the participants and, therefore, the shift in attention toward novel salient phonemes (Key et al., 2005). The P2 component together with the P1, are part of the obligatory components elicited when auditory information is detected and processed by the auditory cortex, and are sensitive to the spectral features of speech (Wagner et al., 2016).

The MMN found when we compared standards and deviants at the first syllable seems to be congruent with the detection of a change in syllabic structure. We observed the same component in Experiment 1. Importantly, we did not observe it when analysing the responses to the first syllable in both standards and deviants in the unpublished data by Monte-Ordoño & Toro (2017b, see Annex 3). In that study, both deviants and standards were CVCVCV nonsense words. It is thus likely that the MMN that emerged at the onset of the CVCCVCCVC deviants in the present study is the result of participants readily detecting a change in syllabic structure.

We also observed a P2-P3 large positivity emerging after the presentation of Rule deviants. This positivity was elicited when comparing Standards to Rule deviants and not when comparing Standards to Syllabic deviants. This suggests that the P2-P3 components were elicited by changes in syllabic structure and the abstract rule.

The significant P300-like component, evident when we compared across deviant stimuli, was thus likely elicited by a rule violation. This violation gave rise to an anterior-central component peaking at around 300 ms. As with the results we observed in Experiment 1, we hypothesize that this positivity could be related to an early P600 or a P3a. Moreover, the emergence of this component, comparable to the one found in Experiment 1 and in Monte-Ordoño & Toro

(2017b), could be taken as further evidence that changes in syllabic structure did not interfere in rule learning.

To sum up, results show that (1) syllabic structure did not interfere with the learnability of a non-adjacent repetition grammar, (2) a MMN in the first syllable signals the detection of a syllabic structure change, and (3) a P300-like positivity signals the detection of a rule violation.

### 3.3.4 Differences Across Rules

In the present study we have explored the neural responses that are triggered by the violation of two repetition-based grammars. The aim was to investigate if syllabic structure interferes with rule learning. Our results suggest that syllabic structure does not interfere with the learnability of a rule based on adjacent or non-adjacent repetitions. Now, we would like to explore the main differences triggered by these different rules.

We thus performed a t-test to assess if there was a difference in performance during the behavioural test between participants presented with the ABB and those presented with the ABA rule. Results show that there was a marginal difference in performance (t(38)=1.76, p=.087), with participants learning more readily the rule based on adjacent repetitions (74.69% of correct responses) than on non-adjacent repetitions (65% of correct responses).

Then, we investigated the differences in neural responses as revealed by ERPs. We performed a series of Block x AP x Position repeated-measures ANOVAs adding Rule (ABB, ABA) as a between-subjects factor, over peak voltages and peak latencies in relevant time windows. These analyses were performed over three components/time windows: the MMN, the P2-P3 components, and the P300-like component. The MMN analysis was performed to confirm that this component was consistent in the two rules. The first syllable was identical in both rules, and we hypothesized that it was elicited by syllabic structure changes. The P2-P3 analysis could provide information on the processing time and peak voltage differences of the combination of change in syllabic structure and rule violation. Finally, the comparisons for the P300-like component would give information on possible differences in rule violations for adjacent and non-adjacent repetitions.

The ANOVA computed over peak voltages for the MMN component we observed after Syllable 1 yielded a main effect of AP (F(1,38)=149.99, p<.001) and Position (F(2,76)=13.47, p<.001). Also, we found the AP x Position interaction significant (F(2,76)=36.62, p<.001). Thus, the AC region had significantly more activity (pairwise interactions: AC and AL, p<.001; AC and AR, p<.001). The ANOVA run over peak latencies revealed a main effect of AP (F(1,38)=4.79, p=.035). Thus, the MMN component was mainly distributed over the AC region (centered at Cz) and was elicited equivalently by both rules. This result is consistent with the distribution of the classical MMN (Näätänen, 2001). Importantly, the fact that the component was elicited by changes in both rules (ABB and ABA) is consistent with the idea that it was triggered by a rapid detection of a change in syllabic structure.

The ANOVA computed over the P2-P3 component in peak voltages revealed a main effect of Rule (F(1,38)=5.55, p=.024). The ABB rule had significantly larger peak voltages than the ABA rule. Moreover, we found a main effect of AP (F(1,38)=110.51, p<.001) and Position (F(2,76)=8.30, p=.002), and showed as significant the interactions AP x Rule (F(1,38)=8.26, p=.007), Block x Position (F(2,76)=5.69, p=.005) and AP x Position (F(2,76)=18.43, p<.001). Examining these results, and including pairwise comparisons, we observed that there is more activity in frontal electrodes in the ABB rule than in the ABA rule (p=.011). Also, that the AC region has the largest amplitudes (AC and AL, p<.001; AC and AR, p<.001), and that in Block 2, the central and right regions have larger amplitudes than the left regions (C and L, p<.001; R and L, p=.008). The ANOVA performed over peak latencies indicated that the ABB rule elicited peak voltages significantly earlier than the ABA rule (ABB, M=243 ms, SE=5, and ABA, M=263 ms, SE=5, Rule, F(1,38)=7.64, p=.009). Moreover, peak voltages were detected earlier in posterior than in anterior regions (AP, F(1,38)=6.42, p=.016), although we did find that in the anterior region peak voltages were detected earlier in the AC region than in the AR region (AP x Position, F(2,76)=3.23, p=.045; pairwise comparisons, AC and AR, p=.030). These results indicate that in the ABB rule, there were larger and earlier responses to a change in rule and syllabic structure. Additionally, these results suggest that the origin of such responses, for both ABB and ABA rules, was in the posterior regions that then migrated to anterior regions and became more intense. Such pattern of neural responses might indicate an engagement of attentional processes likely triggered by the changes in syllabic structure.

Finally, the analysis conducted at the P300 component over peak voltages revealed a main effect of Rule (F(1,38)=37.48, p<.001), AP (F(1,38)=75.63, p<.001) and Position (F(2,76)=6.54, p=.006). The interactions AP x Position and Block x AP were also significant (AP x Position, F(2,76)=11.54, p<.001; Block x AP, F(1,38)=6.83, p=.013). Pairwise comparisons indicated that amplitudes were larger in anterior electrodes (p<.001), particularly in the AC region (AC and AL, p<.001; AC and AR, p=.001). When we performed the analysis at peak latencies, we found no significant effects or interactions. Results show that the ABB rule had larger amplitudes than the ABA rule but both rules had their peak voltages at around 300 ms (ABB, M=309 ms, SE=9; ABA, M= 289 ms, SE=9). These results show that, while rule violations were processed at the same time, the activity was increased in ABB rules when compared to ABA. Comparing these results to the P2-P3 components, we can extrapolate that the rule violation component is elicited in anterior electrodes, while components related to the change in syllabic structure and phonemes come from posterior to anterior electrodes increasing their activity over frontal areas. The activation of frontal areas could be the result of attentional processes (e.g. Escera et al., 2000) engaged by the novel phonemes and syllabic structure present in deviants.

These differences we observe in neural responses to violations of ABB and ABA abstract rules are congruent with the theory of a primitive that is sensitive to adjacent repetitions (Endress et al., 2009). Such proposal has received empirical confirmation from studies with neonates, that learned the rule over ABB and not over ABA nonsense words (Gervain et al., 2008). Additionally, Toro, Sinnett, and Soto-Faraco (2011) reported that adult participants readily generalize adjacent abstract rules (as in ABB) even in the presence of distractors, while find it more difficult to generalize non-adjacent abstract rules (as in ABA). This perceptual mechanism, sensitive to adjacent repetitions, has been proposed to be an automatic process that does not readily respond to non-adjacent repetitions (e.g. Endress et al., 2009). Accordingly, the results we observed suggest higher and earlier activity induced by ABB rules, compared to ABA.

## 3.4 General Discussion

In this study, we assessed the interference of a syllabic structure in the learnability and generalization of a repetition-based adjacent abstract rule (ABB) and a non-adjacent abstract rule (ABA). Results show that there was no impediment in the generalization of the repetition-based grammars when a change in syllabic structure was made between standards and deviants. We observed a late MMN (250 ms) at the onset of the first syllable of deviant stimuli, suggesting a neurophysiological response to a new syllabic structure. An N400-like component suggests the detection of a word-level incongruity elicited after new instances following the standard's rule. Finally, the P300-like component we observed seems to be triggered by rule violations in deviant tokens. Performance in the behavioural tests were well over chance in both experiments, attesting that participants could easily generalize the rule over both repetition-based abstract rules, although performance was slightly better over adjacent repetitions than over non-adjacent ones.

### 3.4.1 Automatic perceptual mechanism for adjacent repetition-based grammars

Electrophysiological responses showed that the violation of an ABB pattern generated earlier and larger responses, in amplitude and over time, than the violation of an ABA pattern. These results are in line with the hypothesis of an automatic perceptual mechanism that is sensitive to identity relations among adjacent tokens (Endress et al., 2009). That is, while rule violation peak voltages in both experiments were elicited at around 300 ms, there was a significant difference in the P2-P3 latencies after Rule deviants. Such differences in electrophysiological responses are further confirmed by the participant's higher performance in the behavioural rule learning test. We observed an average of 75% of correct responses in the experiment assessing ABB rules, compared to an average of 65% of correct responses in the experiment assessing ABA rules. The difference in performances was only marginally significant, suggesting that, although ABB patterns hold an advantage in processing, ABA patterns are still simple enough as to make it possible for participants to learn them.

Moreover, studies in neonates, preverbal infants, and adults have determined that generalizations over abstract adjacent repetitions are easier to learn than over non-adjacent repetitions (Endress et al., 2009; Gervain et al., 2008; Kovács, 2014; Toro, Sinnett, et al., 2011). This difference seems to be of importance in earlier stages of language acquisition, while, still being an advantage, it may be less relevant in adulthood.

### 3.4.2 The MMN as an index of syllabic change

A MMN response was observed after the onset of the deviant word that was very similar (in terms of latency and peak voltage) in both experiments. We hypothesize that this component reflects the mismatch at the syllabic level between standards –that have a CV syllabic structure–, and deviants –that have a CVC syllabic structure. The MMN component has been related to a perceptual mismatch (Näätänen, 2002), as well as to grammar violations (Endress, Dehaene-Lambertz, & Mehler, 2007). In our studies, standards generated an expectancy (a memory trace) at the syllabic level. When we presented a deviant word with a different syllabic structure, a MMN was generated likely due to this incongruence between syllables. In an experiment contrasting words to pseudowords, Shtyrov & Pulvermüller (2002) found that words generated a larger MMN compared to pseudowords. The authors proposed that this could be explained by the activation of a pre-existing long-term memory trace formed by words, as these words were part of the participants' native language. In the Spanish language, CV syllables are far more frequent than CVC syllables (Sandoval et al., 2006). It is thus possible that the memory trace for CV syllables, used in the standards, was quite strong. When a CVC deviant was presented, it was easily detected, not only perceptually but also because its status as a less frequent structure.

### 3.4.3 The N400 as a word-level incongruity component

The N400 component has been reported in the literature either following a fronto-central distribution or a central-parietal distribution. The *classic* N400 is known to be involved in semantic processes and has a centro-parietal distribution (Kutas & Federmeier, 2011; Lau et al., 2008). However, the fronto-centrally distributed N400 elicited in our study has also been reported in second language learning studies, where words are contrasted to orthographically-legal pseudowords (Mclaughlin et al., 2010). In the study by Mclaughlin et al. (2010), naïve language learners elicited an almost native-like centrally-distributed N400 after the presentation of pseudowords, compared to real words. This indicates that only a short period of time is needed to discriminate words from word-like pseudowords (in our study, 40 min). Similarly, a study testing repetition and semantic priming of orthographically legal nonwords found that orthographic and phonological processes were activated and likely triggered an N400 (Deacon et al., 2004). It is thus plausible that the N400-like component we observe in our experiments was elicited by similar processes related to the evaluation of deviant words as congruent items.

The N400-like negativity we observed after Syllabic deviants in the ABB experiment was not replicated in the ABA experiment.

However, in Experiment 2 Figure 12, we can observe that a moderate negativity emerges at around 400 ms. Such negativity is very similar to the one we observed in the ABB study. In the study by Laszlo, Stites, and Federmeier (2012), the authors suggested that the reason why some ERP studies did not find an N400 in response to illegal strings, was because this component tends to be largely more positive in illegal pseudowords than in words. In our study, although we used orthographically legal CVC syllables, a great number of deviant nonsense words would not be considered legal in the Spanish language. It is thus an open issue if the use of a different set of items could facilitate the observation of an N400 in the ABA experiment.

### 3.4.4 The rule violation positivity as an early P600

A positivity spanning from 400 to 600 ms (frequently referred as a late P300 component and an early P600 component), is frequently reported in second language learning studies or artificial grammar studies. In a study about morphosyntactic rule learning, participants were trained in a word-picture association in order to learn to identify stems (nonsense words indicating the animal species in the pictures) and a morphological rule –a suffix indicating gender (Havas et al., 2017). In the recognition phase, when the *stem* did not match the picture, regardless of the correctness of the rule, an N400 emerged. When the rule used was incorrect, regardless of the correctness of the stem, a P600 emerged. This dissociation meant that both processes, the lexical-semantic (lexical learning) and the rule learning mechanism, were independent and worked in parallel. Moreover, the authors conducted a rule generalization task, in which they found that *new* stems following an incorrect rule elicited two positivities, one around 350-400 ms, and the other around 750-900 ms. The earlier time window, in concrete at 330-350 ms, correlated with behavioural data obtained from the rule learning task. They argued that since the stem had no meaning, the only important information was carried by the suffix, and this could have started the morphological analysis at an earlier stage.

In Experiment 1 and 2 in the present study, Rule deviants elicited a P300-like component. They had a different phonemic and syllabic composition from standards, and also followed an incongruent rule. In another study about native grammar processing, participants elicited a P300 and a P600 component after ungrammatical sentences in their native language (Tabullo, Sevilla, Segura, Zanutto, & Wainselboim, 2013). The authors expected to find an early left anterior negativity (ELAN), a signature of phrase structure violations in native languages, but instead they found a P300. They concluded that, since their ungrammatical sentences could have been interpreted as a very infrequent but still acceptable structure, a P300 emerged after the detection of an anomalous element in the sentence. Such response was then followed by a P600 that indicated reanalysis and repair operations. As in Tabullo et al. (2013), it is possible that our P300-like component could have been elicited because Rule deviants were considered anomalous words that formed part of the same nonsense language.

### 3.4.5 Reorientation of attention under divided-attention conditions

The P3a component is elicited by deviant and novel stimuli, and is indicative of a stimulus-driven orientation of attention (Polich, 2007). This component has a maximum amplitude over frontal and central electrodes and usually follows a MMN even after small changes. The N1, MMN and P3a components have been reported in experiments about distractibility and involuntary reorientation of attention after the presentation of deviant or novel sounds in an auditory oddball paradigm (Escera et al., 2000). The N1 and MMN are considered perceptual (pre-attentive) indexes of change-detection, while P3a is regarded as reflecting the actual shift of attention. The amplitude of the P3a is larger for novel than for deviant sounds, hence its amplitude depends on how large is the change between standards and deviants (or novel sounds; Escera et al., 2000). The larger the change, the larger the amplitude of the component.

In our experiments, a change in syllabic structure elicited a MMN at the onset of the word, and a P300-like component was elicited at the onset of the last syllable only for Rule deviants. Since Rule deviants involved a change in the abstract underlying pattern that was not present in Syllabic deviants, it is thus possible that a significant P3a appeared because participants oriented their attention towards the rule violation. In casual questioning the participants after they ran the experiment, they would recall that some word caught their attention, or that at the beginning of the block they would get more distracted. But participants consistently reported that they were paying attention to the silent film, as reflected by their recollection of what happened in this film. It is however possible that watching a silent film was an easy task, and participants were unaware of the attention shifts towards deviant stimuli. An interesting question for further research is whether a more demanding secondary task could prevent such shifts in attention and might therefore prevent the emergence of the positivity we observed in responses to rule violations.

## 3.5 Conclusions

In this chapter, we explored if the learnability of a repetition-based grammar could be interfered by a syllabic structure change under divided-attention conditions. Our results show that learning an adjacent rule (ABB), or a non-adjacent rule (ABA) is not affected by a change in syllabic structure from CVCVCV standards to CVCCVCCVC deviants. A MMN peaking at 250 ms is the electrophysiological response to a change in syllabic structure from standard to deviant words. A P300-like component is elicited after abstract rule violations. Interestingly, violations of ABB rules are detected earlier and with larger amplitudes than violations of ABA rules. The present set of results is congruent with an automatic perceptual mechanism that detects adjacent repetitions.

# Chapter 4

# General Discussion

The aim of this dissertation was to explore if the syllable, an important unit in language, could interfere with basic processes that achieve word segmentation and learning, and the extraction of abstract regularities from speech. In the first experimental section, we reported a series of behavioural experiments. The first set of experiments tackled the issue of the generalization of a repetition-based adjacent rule, instantiated over syllables and over vowels, over different types of syllabic structures. The second set of behavioural studies explored word recognition in a series of statistical learning experiments that involved changes in syllabic structure from familiarization to test. Then, in the second experimental section, we focused on repetition-based grammars. We used an auditory oddball rule learning paradigm and explored the electrophysiological responses that an interference in syllabic structure would elicit after the violation of an adjacent and a non-adjacent repetition rule. Thus, we examined the neural responses to syllabic changes, to abstract rule violations, and the comparison between these responses over adjacent and non-adjacent repetition-based grammars.

In the next sections, I will summarize key results from each chapter. Then, I will discuss some additional points regarding the results we observed, and I will conclude by proposing future lines of research.

## 4.1 Chapter 2 – Summary of findings and further discussion

In Chapter 2, we examined two mechanisms that support language learning and the possible interference of a syllabic structure change. In a series of behavioural studies, we first explored if participants could generalize abstract ABB rules (implemented over syllables and over vowels) when a syllabic structure change took place at the generalization test phase. We presented participants with a short familiarization phase and then a test phase consisting of a 2-AFC test, where different changes in syllabic structure were implemented. Thus, we could examine if there is a concrete type of syllabic structure change that could interfere with the learnability of the abstract grammar. Then, we reported a series of statistical learning experiments. Their aim was to test if participants could recognize words presented in a short familiarization phase in a 2-AFC test that presented words versus part-words. The first condition examined if participants preferred words from part-words when both tokens had a rearrangement of their phonemes in order to change the internal syllabic structure (e.g. from CV to CCV). The second condition, for comparison purposes, presented words and part-words, with no syllabic change (that is, both types of test items had the same syllabic structure as the familiarization items). In the third condition, we tested the participants' discrimination of the original words from their syllable-modified counterparts (that is, we pitted words with the same syllabic structure as the familiarization items against words with a different syllabic structure).

In the first behavioural experiments on rule learning, participants could successfully generalize the rule over any given change in syllabic structure. That is, performance was not affected if, for instance, the rule was implemented during the familiarization phase over words composed by CV syllables and tested with words composed by CCV syllables. There were no significant differences between the generalization over different syllabic structures (Experiments 1 to 3) than over the same syllabic structures (Experiment 4). Further analysis revealed that the listeners were better at extracting rules over syllables than over vowels, thus implying that rule generalization over syllables was not dependent on phonemic segments, as vowels, but it was performed regarding the syllable as a unit. In the second set of experiments on statistical learning, results showed that participants preferred statistically-defined words over part-words during the test, even if these items presented a change in structure. That is, changing syllabic structures did not seem to affect the extraction of statistical regularities as to hinder word identification. Interestingly, the participants did discriminate between words and syllable-modified words. This suggests that the listeners are still able to differentiate between syllabic changes in the present task. Thus, participants showed word learning and good discrimination capabilities.

### 4.1.1 The Syllable as an organizing unit

We have argued that the syllable is a crucial unit in language. In previous sections, we reviewed recent evidence suggesting that syllable-like chunks are the preferred segmentation unit over continuous speech streams expressed by a computational model based on the basic rhythms carried by the speech stream, prior to any linguistic knowledge (Räsänen et al., 2018). Moreover, this study was congruent with the evidence that neonates and human adults use the same strategy to segment a continuous stream into its constituent words by discriminating between the initial and the final syllable in these words (Teinonen et al., 2009). These pieces of evidence, along with previous psycholinguistic studies, pointed to the syllable being the main linguistic unit of segmentation (Cutler et al., 2001; Mehler, 1981; Segui et al., 1981). Additionally, the syllable has been considered the preferred unit in speech production (Wijnen, 1988). There is an evolutionary view, captured by the motor theory of speech perception and articulatory phonology, that states that syllable-sized vocalizations together with hand gestures gave place to speech (Gentilucci & Corballis, 2006). Evidence in favour of this evolutionary view is the results from a combined

EEG/fMRI study that recorded participants at rest and watching a movie to explore which brain regions correlated with activity in the frequency bands corresponding to the syllabic and the phonemic rate (Morillon et al., 2010). Results showed that delta-theta and gamma oscillations, corresponding to the syllabic and the phonemic rates, were observed in the language system, but not in motor or visual control areas. This suggested that these rhythms play an important role in speech processing. Moreover, the authors showed that speech-related rhythms were found in the motor hand area and interacted with the left auditory cortex at the syllabic rate, but not at the phonemic rate. Jaw movements vibrate at the frequency rate of 4 Hz, which corresponds to the syllabic rate, and is congruent with the evolutionary theory that there is an auditory-motor tuning to the syllabic rate. However, a language-specific maturation from auditory-motor areas is needed to achieve fine-grained articulatory performance for phonemic rates. That is, while syllabic rates are embedded in the evolutionary picture and naturally vocalized and segmented by young infants, fine-grained phonemic specialization comes with language-related expertise. Thus, there are consistent results supporting the importance of the syllable as a main organizing unit during language processing. However, we failed to find any modulation of a syllabic structure change in rule learning and in statistical learning. Below we will suggest some possible explanations for this.

### 4.1.2 Primitives and Distinct Strategies in SL and RL

The mechanisms that underlie rule learning and statistical learning are intrinsically different, and operate on different levels. Rule learning is based on token-independent abstractions, while statistical learning is defined over token-specific instances. Thus, there are different reasons why a syllabic structure change might not have modulated the operation of these mechanisms.

In the rule learning experiments, we used a very simple grammatical rule, an adjacent repetition-based pattern (as in ABB). We have argued that perceptual constraints play an important role in speech processing. Importantly, Endress, Nespor, and Mehler (2009), suggested the existence of a primitive sensitive to adjacent repetitions, that is, a perceptual bias that makes adjacent repetitions be readily detected by the brain. This primitive is congruent with ABB pattern generalization experiments, where neonates, young infants, and adults can easily detect the pattern (Endress et al., 2007; Gervain et al., 2008; Kovács, 2014). It is thus possible that the computational load induced by a change in syllabic structure over such grammars may not be challenging enough as to prevent successful generalization of the rule. This seems to be the case even for rules implemented over vocalic segments. If so, one could think that a more challenging option would be to test the interference of syllabic structure change in a more complex grammar (e.g. recursive grammars). Maybe, by increasing the complexity of the grammar tested we could observe effects of syllabic structure. However, there is another possible explanation for the fact that participants were able to generalize abstract rules even over changes in syllabic structures. By definition, abstract rules are token-independent. That is, they are defined by the relations established between the elements that instantiate them, not by the specific elements themselves. It is thus possible that listeners in our experiments were in fact learning a really token-independent rule (ABB) defined by the repetition of the second and third elements. The fact that these specific elements could be instantiated over a CCV or a CVC syllabic structure might thus be irrelevant. If this is the case, one could think of experiments with more complex abstract grammars in which we still do not observe any effect of syllabic structure. As long as the to-be-learned regularity is defined over relationships, and not over elements, syllabic structure might not affect the resulting process.

In the statistical learning experiments, we rearranged the phonemes composing the words from the stream to create the novel syllabic structure we tested. This rearrangement was made following the phonotactics of the Spanish language, and by exchanging the second consonant with the first vowel in each word (e.g. p**e-l**a-ti, a CVCVCV word, was transformed into p**le-**a-ti, a CCVVCV word). Surprisingly, our results showed that this change did not affect the recognition of the word from the stream. Moreover, participants could perfectly tell apart a word from a syllable-modified word (with a mean performance of 89%). Results from developmental psychology show that even before the first year of life infants are able to recognize words that maintain the information in their consonant tier intact (e.g. Hochmann, Benavides-Varela, Nespor, & Mehler, 2011). This is in line with the hypothesis that consonants play an important role in word identification, while vowels are preferred to extract regularities from the signal (see Bonatti, Peña, Nespor, & Mehler, 2005; Mehler, Peña, Nespor, & Bonatti, 2006; Nespor, Peña, & Mehler, 2003; Toro, Shukla, Nespor, & Endress, 2008). In our experiments, the information carried by the consonant tier was left intact across syllabic structure changes. That is, the CVCVCV word *pelati* was transformed into the CCVVCV word *pleati*. Even though their syllabic structures were different, both nonsense words shared the consonant sequence p-l-t. Because statistical computations have been shown to be preferentially computed over consonants than over vowels, it is possible that participants in our experiments were in fact storing information about consonant sequences (as in p-l-t). If so, this consonant information would be preserved during the test (even if the syllabic structure changed) leading to the correct word identification we observed. If so, this would provide support to the idea that statistical information is given more weight than syllabic information to identify the words.

Moreover, it has been shown that the first consonant plays a more important role than the second consonant in lexical access. Eleven-month-old infants recognize a word with a change in the second consonant but do not recognize it if the change is in the first consonant (e.g. word was *bubbles*, with first consonant change *mubbles*, and with second consonant change *bummles*; Vihman, Nakai, DePaolis, & Hallé, 2004). This result is in line with the idea that there is a primitive, sensitive to edge-positioned instances, that makes readily accessible variables on edge positions but not variables in middle positions (Endress et al., 2009) and congruent with ERP speech segmentation studies that show that the initial and final syllables of words are key in word segmentation. This has been proven in neonates and human adults (e.g. Sanders, Newport, & Neville, 2002; Teinonen et al., 2009), confirming the automaticity of this mechanism. By preserving the information in the beginning of the sequence we might have facilitated the task of word identification. To test this possibility one might think of experiments in which test items do not include the first phonemes from familiarization items.

## 4.2 Chapter 3 – Summary of findings and further discussion

In Chapter 3, we explored the electrophysiological responses triggered by a change in syllabic structure during the generalization of an adjacent and a non-adjacent repetition-based grammar. This was conducted over an auditory oddball paradigm that presented trisyllabic CVCVCV standards following either an ABB or an ABA pattern over syllables. We created two types of deviants: syllabic deviants, that were formed by new phonemes and a new syllabic structure (a CVC structure), and rule deviants, that were formed by new phonemes, new syllabic structure and a new rule (a diversity-based ABC rule). Syllabic and rule deviants only differed in the rule they were instantiating. We examined responses at each syllable within the words. At the onset, we explored brain components elicited by a change in syllabic structure, while at the third syllable we explored brain responses after rule violations.

### 4.2.1 MMN as a syllabic structure change detector

At the onset of the words, electrophysiological responses after deviants showed a MMN congruent with syllabic structure changes. This result was invariant in latency and in amplitude over all deviants and across the adjacent and the non-adjacent grammar. In fact, we were expecting it to be invariant across grammars, since both grammars had the same first and second syllables. The grammars only differed in the third syllable (e.g. an ABB syllabic deviant word was *puncarcar*, and the ABA syllabic deviant equivalent was *puncarpun*, see Annex 2 and 3). The MMN is a perceptual change detector component, independent of attention, that is elicited by a mismatch between a standard frequent stimuli, that generates a memory trace, and a sporadic deviant stimuli, that can be different from the standard by its physical properties (such as pitch), or by more complex abstract relations (Näätänen, 2001; Näätänen, Paavilainen, Alho, Reinikainen, & Sams, 1989). Hence, the MMN can be used as an index of linguistic stimuli discrimination, since it can be elicited by subtle changes in phoneme contrasts and syllables (Näätänen, 2001).

Therefore, the MMN is a pre-attentive perceptual mechanism that seems to be triggered by the automatic detection of subtle changes in the stimuli. In our experiment, such change seems to be linked to the syllabic structures of our stimuli, suggesting that its detection was done readily and likely in an automatic manner. This provides further support to the idea of the syllable as a main organizing unit in speech, as subtle changes in syllabic structure are rapidly detected.

### 4.2.2 Components related to rule violations

When we examined the neural responses triggered by the third syllable, we observed that rule violations elicited a P300 component. Comparison results for the P300 component between the ABB and the ABA experiments showed larger and earlier activity induced in the adjacent compared to the non-adjacent grammar. These results are congruent with a perceptual primitive

that is sensitive to only adjacent repetitions (Endress et al., 2009). There was also a marginal difference in behavioural performance between participants in the adjacent and in the non-adjacent grammar, further supporting an advantage for the processing of an ABB pattern in comparison to the ABA rule.

Our study used an auditory oddball paradigm in which participants were actively ignoring the stimuli and attending a silent film. However, participants showed indications of involuntary shifts of attention towards deviant foils, particularly rule deviants, as indicated by first, a pre-attentive MMN at the onset of the syllable, and then the emergence of a P300, specifically known as P3a (Escera, Alho, Schröger, & Winkler, 2000). The P3a component indicates a reorientation of attention towards deviant and novel stimuli (Escera et al., 2000; Escera & Corral, 2007). Syllabic deviants did not elicit a P3a, thus indicating that changes after rule deviants were more salient for the listeners. Yet, the P300 is not a component that has a direct relation to rule violations. It is an indirect measure of rule violation, and this is colloquially known as *hijacking* an ERP component (Luck, 2005). In this sense, it may be possible that there is not one specific component that can be related to rule violation, since it seems to be highly dependable on the complexity of the stimuli and task attentional demands. For instance, rule violations over tones that violate a frequency rule elicit a MMN (in ABB and ABA patterns, Endress et al., 2007), while there are other rule violations that  elicit an N400 component. As we have mentioned before, the N400 is a component that has been related to lower levels of lexical processes, such as lexical access, and also semantic processes (Mueller et al., 2008). The N400 component can be elicited by semantic-free foils and is known to be an indirect index of word segmentation (Luck, 2005; Mueller et al., 2008). However, the N400 has also been found as an indirect rule violation index, in active listening studies, where nonce word repetition was high and the number of nonce words was quite small, thus possibly inducing word learning (words following an ABB and ABA rules over syllables, Sun, Hoshi-Shiba, Abla, & Okanoya, 2012), and in a study using a miniature version of the Japanese language with semantic-free words that violated a grammatical rule (a suffix, Mueller et al., 2008).

It is likely then, that there is no one rule violation component but several components that serve as indirect indexes of rule violation and are dependent on the stimuli number, repetition and complexity, and on the attentional demands of the task. In the present study, the P3 component seems to indicate the detection of a change in the abstract rule. This is because it was only triggered by deviant stimuli that changed the rule, and not by deviant stimuli that implemented the same rule as standards.

## 4.3 Future Directions

In the present dissertation we have examined the influence of syllabic structure over statistical learning in a set of behavioural experiments. We have also examined the influence of different types of syllabic structure over the learning of adjacent repetition-based grammars, and finally, the influence of syllabic structure over adjacent and non-adjacent repetition-based grammars in an ERP study using the auditory oddball paradigm.

Syllabic structure change did not interfere with statistical learning or rule learning. Also, we found evidence that syllabic structure change was detected very early after the stimulus onset, eliciting a MMN. In Monte-Ordoño and Toro (2017), they presented participants with an auditory oddball paradigm with standards following an ABB rule either on the consonants (Consonant condition) or on the vowels (Vowel condition). Deviant stimuli were created with new phonemes and could be of two types: phoneme deviants, followed the same rule as standards, and rule deviants, followed a different rule than standards. Results in the Consonant and Vowel condition showed a MMN after phoneme and rule deviants, although the MMN in the Vowel condition was less pronounced, and they found an N400 after rule violations in the vowel condition. Thus, the authors argued that participants were applying different strategies possibly due to the different roles consonants and vowels play in language, showing that consonants have more weight on lexical decisions, while vowels are preferred to extract regularities (Bonatti et al., 2005; Nespor et al., 2003; Toro, Nespor, et al., 2008). In the vowel condition, participants could successfully extract the rule, while in the consonant condition although participants showed behavioural success in extracting the regularity, their electrophysiological responses indicated an inefficient strategy. It has been shown that extracting regularities over consonants is very challenging (Toro, Nespor, et al., 2008). It could thus be interesting to test whether making the rule learning experiment harder would allow for the observation of syllabic structure effects. That is, it might be the case that rule learning over consonants would be interfered by a syllabic structure change. If so, it would suggest that it is the automaticity of the rule learning process what might prevent to observed effect of syllabic structures. Alternatively, as we mentioned above, it could be the case that the very nature of token-independent abstract rules prevents any modulation by syllabic structures. One could think of an experiment in which the target grammar is much more complex (as in a center-embedding grammar for example) and in which one changes the syllabic structure from familiarization to test. If the operation to extract such regularities is truly token-independent (that is, if it operates over variables), then we should not observe any effect of syllabic structure.

Another possible line to follow the study of syllabic structures during rule learning would be to explore the use of heterogeneous syllabic structures that follow an underlying abstract regularity. One could think of an experiment in which we implement an ABA abstract regularity over syllabic structures as in CVC CV CVC or in CCV CV CCV. That is, what defines the different variables composing the rule is the structure of their syllables. Since syllables are an important processing unit, implementing regularities over them, could be a possible way to induce proper linguistic categorization. Alternatively, the combination of such different syllabic structures might interact with linguistic constraints that forbid such combinations and make rule learning highly difficult as in the case of syntactic categories (Endress & Hauser, 2009).

In our statistical learning experiments, we changed the syllabic structure of the word by exchanging two phonemes within the word, as in *g**o-l**u-ne* would change to *g**lo-**u-ne.* With this change, we saw that we preserved transitional probabilities between segments (that is, we preserved the information at the consonant and the vocalic tiers) and that the change in the second consonant did not impair word recognition. However, participants could clearly discriminate that words and syllable-modified words were different than part-words, since the two former had the same transitional probabilities between their segments. Here, there are several questions that could be explored by further experiments: how much could we modify a word before it stopped being identified as a proxy for words presented in the stream? Since experiments on word segmentation have shown the importance of initial and final syllables to detect word boundaries (Räsänen et al., 2018; Teinonen & Huotilainen, 2012), as well as the existence of a perceptual primitive that is sensitive to edge positions (Endress et al., 2009), one could think of an experiment in which we suppress the middle syllable of test items. If participants are focusing on the first phonemes to tell apart words from part-words, we should be able to still observe correct word identification in the absence of middle syllables. If, on the contrary, participants are really relying on the high transitional probabilities present between segments, independently of syllabic structure, we should not see correct word recognition under such conditions. Similarly, would adding several phonemes between the initial and final syllable give the same outcome? The present set of experiments opens the door to this further empirical questions.

## 4.4 Summary and Conclusions

In this dissertation we sought to explore the influence of syllabic structure on basic mechanisms of language learning, by the use of behavioural and electrophysiological approaches.

In Chapter 2, we presented a series of behavioural studies exploring the interference of a syllabic structure change over an ABB rule implemented over syllables and over vowels, and using different syllabic structures. Then, we explored the interference of syllabic structure in a series of statistical learning experiments. We arrived at the following conclusions:

- Extraction of regularities was easier over syllables than over vowels in adjacent repetition-based grammars (ABB). This suggests that the syllable has a prominent role as the organizing unit in speech processing.
- Syllabic structure change did not interfere in rule learning, independently of the type of syllabic structure used.
- Syllabic structure did not interfere in statistical learning, and participants could discriminate between the words from the stream and the syllable-modified words.

In Chapter 3, we explored the electrophysiological responses triggered by the interference of syllabic structure on the learnability of adjacent and non-adjacent repetition-based grammars. We concluded that:

- The index of syllabic structure change is the MMN component. It appears after deviants in the first syllable. It remains unchanged across rules.
- A P300 component is triggered by rule violations. This component appears earlier and with larger amplitudes after violations in the ABB pattern, signalling a more readily response to adjacent than to non-adjacent repetitions, and congruent with the theory of a perceptual primitive that is sensitive to adjacent repetitions.
- There is no interference of syllabic structure over the processing of adjacent and non-adjacent regularities. Participants have higher performances over adjacent than over non-adjacent patterns, although their difference is marginal.

To summarize, the learnability of abstract adjacent or non-adjacent repetition-based grammars and statistical learning are not interfered by a change in the syllabic structure of the constituent words. A syllabic structure change is readily detected a few hundred milliseconds after the presentation of the stimulus, manifesting the automatic perceptual nature of its detection.

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# ANNEX 1

Data from Chapter 2 Experiment 1 to 5.

**Table 1.** Words presented during the familiarization phase in Experiment 1, 3 and 4, from the Syllable Condition. Forty-five words were created for the familiarization phase. Words followed an ABB rule on the syllables.

| **Familiarization** | | |
|---|---|---|
| febibi | fimeme | fomimi |
| femimi | fitoto | fodede |
| fedodo | fidodo | fobebe |
| befifi | bimomo | bofefe |
| bemomo | bifefe | botiti |
| betoto | bitoto | botete |
| mefofo | mitete | mobibi |
| medidi | mifofo | motiti |
| mebobo | midede | motete |
| demomo | difefe | domeme |
| detiti | dibobo | dobibi |
| defifi | difofo | dofifi |
| tebobo | tibebe | tomeme |
| temimi | tidede | tobebe |
| tedidi | tidodo | todidi |

**Table 2.** Words presented during the familiarization phase in Experiment 2, from the Syllable Condition. Thirty-six words were created for the familiarization phase. Words followed an ABB rule on the syllables.

| **Familiarization** | | |
|---|---|---|
| nergilgil | nircelcel | norpelpel |
| relpinpin | rilgengen | rolcencen |
| gelnirnir | girnelnel | gorlenlen |
| cerlinlin | cinlerler | conrelrel |
| penrilril | pilrenren | polnerner |
| lencircir | linperper | longerger |
| nelporpor | nilgorgor | nolgirgir |
| rencolcol | rinpolpol | ronpilpil |
| genrolrol | gilronron | gonlirlir |
| celnornor | cirnolnol | colrinrin |
| perlonlon | pinlorlor | pornilnil |
| lergongon | lirconcon | lorcincin |

**Table 3.** Words presented at the behavioural test from Experiment 1. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the syllables.

| Rule words | Non-Rule words |
|---|---|
| canpurpur | cangulpar |
| garculcul | garpuncal |
| palgungun | palcurgan |
| cargulgul | carpungal |
| guncalcal | gunparcul |
| purcancan | purgalcun |
| culparpar | culganpur |
| pulgangan | pulcargun |

**Table 4.** Words presented at the behavioural test from Experiment 2. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the syllables.

| Rule words | Non-Rule words |
|---|---|
| fabubu | famuba |
| bamumu | baduma |
| madudu | matuda |
| datutu | dafuta |
| budada | bufadu |
| mutata | mubatu |
| dubaba | dutabu |
| tufafa | tumafu |

**Table 5.** Words presented at the behavioural test from Experiment 3. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the syllables.

| Rule words | Non-Rule words |
|---|---|
| pragluglu | praclugra |
| gracluclu | graplucra |
| plagrugru | placrugla |
| claprupru | clagrupla |
| gluprapra | glucraplu |
| cruglagla | cruplagru |
| gruplapla | gruclapru |
| plucracra | plugraclu |

**Table 6.** Words presented at the behavioural test from Experiment 4. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the syllables.

| Rule words | Non-Rule words |
|---|---|
| naruru | napura |
| ragugu | ranuga |
| palulu | parula |
| gapupu | galupa |
| nupapa | nugapu |
| rulala | runalu |
| gunana | guranu |
| lugaga | lupagu |

**Table 7.** Words presented during the familiarization phase in Experiment 1, 3 and 4, from the Vowel Condition. Forty-five words were created for the familiarization phase. Words followed an ABB rule on the vowels.

| **Familiarization** | | |
|---|---|---|
| febiti | fimede | fomiti |
| femidi | fitomo | fodete |
| fedoto | fidobo | fobeme |
| befidi | bimodo | bofete |
| bemofo | bifeme | botimi |
| betodo | bitofo | botefe |
| mefoto | mitefe | mobidi |
| medifi | mifobo | motifi |
| mebodo | midebe | motede |
| demobo | difete | domebe |
| detifi | diboto | dobimi |
| defibi | difomo | dofiti |
| tebomo | tibefe | tomebe |
| temibi | tideme | tobede |
| tedimi | tidofo | todibi |

**Table 8.** Words presented during the familiarization phase in Experiment 2, from the Vowel Condition. Thirty-six words were created for the familiarization phase. Words followed an ABB rule on the vowels.

| **Familiarization** | | |
|---|---|---|
| gencirpil | gincerpel | goncelper |
| gerpincil | girpencel | golpercen |
| celpirgin | cilgerpen | congelper |
| cergilpin | cirpelgen | corpengel |
| pengilcir | pingelcer | polcergen |
| pelcingir | pilcenger | porgencel |
| gelponcor | gincolpor | golcinpir |
| gercolpon | gilporcon | gorpilcin |
| cenporgol | cinpolgor | congirpil |
| celgonpor | cirgonpol | colpingir |
| pengorcol | pilgorcon | pongircil |
| percolgon | pircongol | porcilgin |

**Table 9.** Words presented at the behavioural test from Experiment 1. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the vowels.

| Rule words | Non-Rule words |
|---|---|
| canpurgul | cangurpal |
| garculpun | garpulcan |
| palguncur | palcungar |
| cargulpun | carpulgan |
| guncalpar | gunpalcur |
| purcangal | purgancul |
| culpargan | culgarpun |
| pulgancar | pulcangur |

**Table 10.** Words presented at the behavioural test from Experiment 2. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the vowels.

| Rule words | Non-Rule words |
|---|---|
| fabumu | famuba |
| batudu | baduta |
| dafutu | datufa |
| tamubu | tabuma |
| fubata | futabu |
| mufada | mudafu |
| dutaba | dubatu |
| tudafa | tufadu |

**Table 11.** Words presented at the behavioural test from Experiment 3. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the vowels.

| Rule words | Non-Rule words |
|---|---|
| praglucru | praclugra |
| graclupru | graplucra |
| plagruclu | placrugla |
| clapruglu | clagrupla |
| glucrapla | glupraclu |
| cruglapra | cruplagru |
| gruplacra | gruclapru |
| plucragla | plugraclu |

**Table 12.** Words presented at the behavioural test from Experiment 4. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the vowels.

| Rule words | Non-Rule words |
|---|---|
| narupu | napura |
| rapugu | ragupa |
| panulu | paluna |
| galunu | ganula |
| nurala | nularu |
| rulaga | rugalu |
| gunapa | gupanu |
| lupara | lurapu |

# ANNEX 2

## Data from Chapter 3, Experiment 1, ABB rule learning with ERPs

**Table 13.** Words presented during the familiarization phase of the ERP experiment. Forty-five standards and one-hundred forty-four deviants (72 Syllabic and 72 Rule) were presented to participants at each block. Standard words were repeated 11 times within each block. Standard and Syllabic deviants followed an ABB rule and Rule deviants followed an ABC rule on the syllables.

| Standard | | Syllabic deviant | | Rule deviant | |
|---|---|---|---|---|---|
| febibi | mobibi | pancuncun | puncarcar | pancungal | puncarlur |
| femimi | motiti | pangungun | pungalgal | pangunnar | pungalnul |
| fedodo | motete | panlurlur | punnalnal | panlurgal | punnalcul |
| befifi | domeme | panrulrul | punranran | panrulnar | punrangur |
| bemomo | dobibi | parculcul | purcancan | parculral | purcanrul |
| betoto | dofifi | pargurgur | purgalgal | pargurcan | purgalcun |
| mefofo | tomeme | parlunlun | purlanlan | parluncal | purlangur |
| medidi | tobebe | parnulnul | purnalnal | parnullan | purnallun |
| mebobo | todidi | palculcul | pulcalcal | palculran | pulcalrun |
| demomo | | palgurgur | pulgangan | palgurlan | pulgannur |
| detiti | | palnurnur | pulnarnar | palnurgar | pulnarlun |
| defifi | | palrunrun | pulralral | palruncan | pulralcur |
| tebobo | | gancurcur | guncancan | gancurral | guncannur |
| temimi | | ganpulpul | gunpalpal | ganpulnar | gunpallur |
| tedidi | | gannurnur | gunlarlar | gannurpal | gunlarrul |
| fimeme | | ganrunrun | gunnarnar | ganrunlar | gunnarpul |

| | | | | |
|---|---|---|---|---|
| fitoto | garculcul | gurcarcar | garculnal | gurcarrun |
| fidodo | garpulpul | gurparpar | garpulran | gurparlun |
| bimomo | garlurlur | gurlanlan | garlurgal | gurlanpul |
| bifefe | garrunrun | gurnalnal | garrunpan | gurnalcul |
| bitoto | galpunpun | gulcalcal | galpungan | gulcalrun |
| mitete | galpurpur | gulpanpan | galpurlan | gulpancur |
| mifofo | galnulnul | gulralral | galnulpar | gulralpun |
| midede | galrulrul | gulranran | galrulgan | gulrannur |
| difefe | nalcuncun | nulcarcar | nalcunpar | nulcarpun |
| dibobo | nalgulgul | nulgangan | nalgullar | nulgancur |
| difofo | nalpunpun | nulpanpan | nalpunral | nulpangur |
| tibebe | nalpurpur | nulpalpal | nalpurcar | nulpalpur |
| tidede | nallurlur | nullarlar | nallurpal | nullarrun |
| tidodo | nalrulrul | nulralral | nalrulcan | nulrallun |
| fomimi | narcurcur | nurcalcal | narcurpan | nurcalpun |
| fodede | nargungun | nurgargar | nargunnal | nurgarrul |
| fobebe | nargulgul | nurparpar | nargulran | nurparpun |
| bofefe | narpulpul | nurlanlan | narpullar | nurlangul |
| botiti | narlurlur | nurralral | narlurran | nurralgun |
| botete | narrunrun | nurranran | narrunlar | nurrancul |

**Table 14.** Words presented at the behavioural test. Rule words and Non-Rule words differed only in the third syllable. Rule words followed an ABB rule and Non-Rule words followed an ABC rule over the syllables.

| Rule words | Non-Rule words |
|---|---|
| ramlesles | ramlessor |
| mersalsal | mersalros |
| somrelrel | somrellas |
| losmarmar | losmarsem |
| rolmesmes | rolmeslam |
| sarmolmol | sarmolles |
| roslemlem | roslemsal |
| melrasras | melrassol |
| lemrosros | lemrosmar |
| malsorsor | malsorler |
| semlorlor | semlormal |
| lamserser | lamserros |
| salmormor | salmorres |
| moslarlar | moslarlem |
| lersamsam | lersamrol |
| lasremrem | lasremmol |

**Table 15.** Percentage of correct responses at the 2-AFC behavioural test passed after the ERP experiment to assess if participants learned the ABB rule embedded in syllables.

| **Participant number** | **% of correct responses** | **Participant number** | **% of correct responses** |
|---|---|---|---|
| 1 | 93.75 | 11 | 81.25 |
| 2 | 43.75 | 12 | 100 |
| 3 | 81.25 | 13 | 56.25 |
| 4 | 62.50 | 14 | 75 |
| 5 | 68.75 | 15 | 81.25 |
| 6 | 68.75 | 16 | 75 |
| 7 | 100 | 17 | 93.75 |
| 8 | 56.25 | 18 | 75 |
| 9 | 87.50 | 19 | 68.75 |
| 10 | 43.75 | 20 | 81.25 |

# ANNEX 3

Data from Chapter 3, Experiment 2, ABA rule learning with ERPs.

**Table 16.** Words presented during the familiarization phase of the ERP experiment. Forty-five standards and one-hundred forty-four deviants (72 Syllabic and 72 Rule) were presented to participants at each block. Standard words were repeated 11 times within each block. Standard and Syllabic deviants followed an ABA rule and Rule deviants followed an ABC rule on the syllables.

| Standard | | Syllabic deviant | | Rule deviant | |
|---|---|---|---|---|---|
| febife | mobimo | pancunpan | puncarpun | pancungal | puncarlur |
| femife | motimo | pangunpan | pungalpun | pangunnar | pungalnul |
| fedofe | motemo | panlurpan | punnalpun | panlurgal | punnalcul |
| befibe | domedo | panrulpan | punranpun | panrulnar | punrangur |
| bemobe | dobido | parculpar | purcanpur | parculral | purcanrul |
| betobe | dofido | pargurpar | purgalpur | pargurcan | purgalcun |
| mefome | tometo | parlunpar | purlanpur | parluncal | purlangur |
| medime | tobeto | parnulpar | purnalpur | parnullan | purnallun |
| mebome | todito | palculpal | pulcalpul | palculran | pulcalrun |
| demode | | palgurpal | pulganpul | palgurlan | pulgannur |
| detide | | palnurpal | pulnarpul | palnurgar | pulnarlun |
| defide | | palrunpal | pulralpul | palruncan | pulralcur |
| tebote | | gancurgan | guncangun | gancurral | guncannur |
| temite | | ganpulgan | gunpalgun | ganpulnar | gunpallur |
| tedite | | gannurgan | gunlargun | gannurpal | gunlarrul |

| | | | | |
|---|---|---|---|---|
| fimefi | ganrungan | gunnargun | ganrunlar | gunnarpul |
| fitofi | garculgar | gurcargur | garculnal | gurcarrun |
| fidofi | garpulgar | gurpargur | garpulran | gurparlun |
| bimobi | garlurgar | gurlangur | garlurgal | gurlanpul |
| bifebi | garrungar | gurnalgur | garrunpan | gurnalcul |
| bitobi | galpungal | gulcalgul | galpungan | gulcalrun |
| mitemi | galpurgal | gulpangul | galpurlan | gulpancur |
| mifomi | galnulgal | gulralgul | galnulpar | gulralpun |
| midemi | galrulgal | gulrangul | galrulgan | gulrannur |
| difedi | nalcunnal | nulcarnul | nalcunpar | nulcarpun |
| dibodi | nalgulnal | nulgannul | nalgullar | nulgancur |
| difodi | nalpunnal | nulpannul | nalpunral | nulpangur |
| tibeti | nalpurnal | nulpalnul | nalpurcar | nulpalpur |
| tideti | nallurnal | nullarnul | nallurpal | nullarrun |
| tidoti | nalrulnal | nulralnul | nalrulcan | nulrallun |
| fomifo | narcurnar | nurcalnur | narcurpan | nurcalpun |
| fodefo | nargunnar | nurgarnur | nargunnal | nurgarrul |
| fobefo | nargulnar | nurparnur | nargulran | nurparpun |
| bofebo | narpulnar | nurlannur | narpullar | nurlangul |
| botibo | narlurnar | nurralnur | narlurran | nurralgun |
| botebo | narrunnar | nurrannur | narrunlar | nurrancul |

**Table 17**. Words presented at the behavioural test. Rule words and Non-Rule words differed only in the third syllable. Rule words followed an ABA rule and Non-Rule words followed an ABC rule over the syllables.

| Rule words | Non-Rule words |
|---|---|
| ramlesram | ramlessor |
| mersalmer | mersalros |
| somrelsom | somrellas |
| losmarlos | losmarsem |
| rolmesrol | rolmeslam |
| sarmolsar | sarmolles |
| roslemros | roslemsal |
| melrasmel | melrassol |
| lemroslem | lemrosmar |
| malsormal | malsorler |
| semlorsem | semlormal |
| lamserlam | lamserros |
| salmorsal | salmorres |
| moslarmos | moslarlem |
| lersamler | lersamrol |
| lasremlas | lasremmol |

**Table 18.** Percentage of correct responses in the 2-AFC behavioural test assessed after the ERP experiment to assess if participants learned the ABA rule embedded over syllables.

| Participant number | % of correct responses | Participant number | % of correct responses |
|---|---|---|---|
| 1 | 43.75 | 11 | 68.75 |
| 2 | 62.50 | 12 | 56.25 |
| 3 | 68.75 | 13 | 100 |
| 4 | 50 | 14 | 50 |
| 5 | 75 | 15 | 68.75 |
| 6 | 62.50 | 16 | 62.50 |
| 7 | 18.75 | 17 | 62.50 |
| 8 | 62.50 | 18 | 75 |
| 9 | 100 | 19 | 87.50 |
| 10 | 62.50 | 20 | 62.50 |

# ANNEX 4

Data analysis from Syllable 1 of Monte-Ordoño and Toro (2017). Cluster-based permutations tests over Standard and Phoneme deviants (Figure 15), and Standards and Rule deviants (Figure 16) yielded no significant time windows.

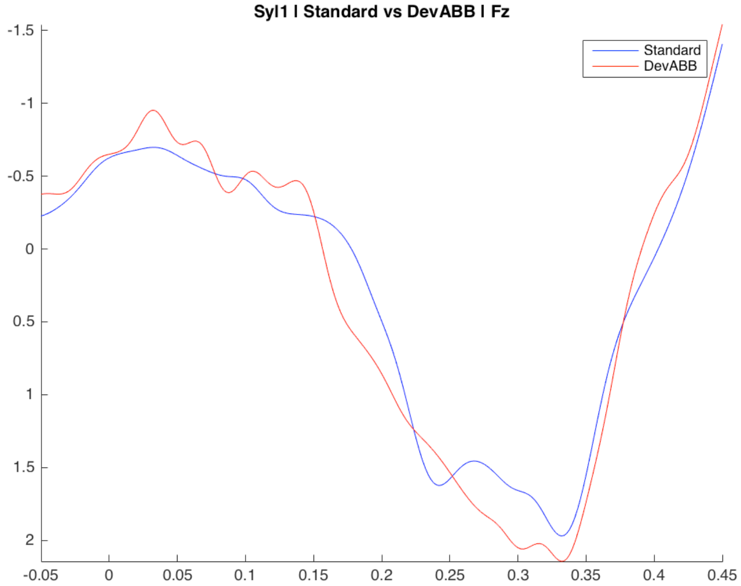

**Figure 15.** Grand average of the ERPs from standards and phoneme deviants at the first syllable. We can observe that between standards and deviants we do not find any significant difference. Data obtained from the authors (see Monte-Ordoño & Toro, 2017b)

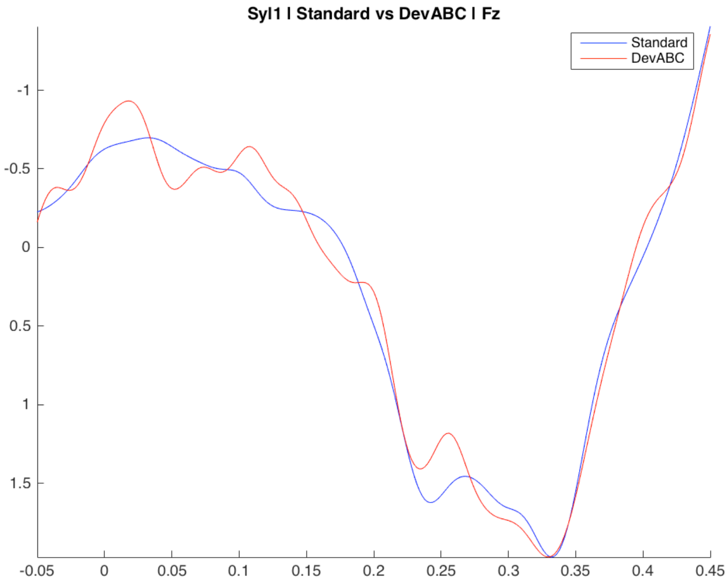

**Figure 16.** Grand average of the ERPs from standards and rule deviants from the first syllable. We can observe that between standards and deviants we do not find any significant difference. Data obtained from the authors (see Monte-Ordoño & Toro, 2017b)