NEURAL MECHANISMS OF ABSTRACT RULE CHANGES IN SPEECH: EXPLORING PHONOLOGIC AND ATTENTIONAL CONSTRAINTS

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I DE LA SALUT

Als meus pares.

“Words are, in my not-so-humble opinion, our most inexhaustible source of magic. Capable of both inflicting injury, and remedying it.”

- Albus Dumbledore, *Harry Potter and the Deathly Hallows*

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RESUM

L’extracció de regles de la parla és crucial per a l’adquisició del llenguatge. La present dissertació estudia el mecanisme d’aprenentatge de regles explorant com el cervell detecta regularitats rellevants dins del senyal lingüístic. Per tal de donar resposta a aquesta pregunta he seguit tres línies de recerca. En primer lloc m’he centrat en la detecció de canvis, tant superficials com estructurals, de les regles lingüístiques. Mitjançant l’estudi dels potencials evocats, aquesta primera línia explora les respostes neuronals desencadenades després d’una violació estructural. En segon lloc, he estudiat els efectes de la manipulació fonètica amb la intenció de descobrir si les respostes neuronals associades a l’aprenentatge de regles varien quan aquestes s’implementen sobre les vocals o sobre les consonants. És a dir, m’he centrat en avaluar com les diverses categories fonètiques poden donar lloc a respostes neuronals diverses. En tercer lloc, he explorat la detecció de regles en un context d’aprenentatge heterogeni per tal d’observar com poden ser descobertes les regles abstractes dins d’un senyal sorollós. En conjunt, els resultats obtinguts mostren que la manipulació d’ambdós factors, tant de les pistes fonològiques com del context d’aprenentatge, modula el procés d’extracció de regles. Més específicament, aquestes manipulacions podrien alterar les fonts d’informació que es prioritzen durant el processament de la parla. Finalment, la presència d’una pista diferenciadora del senyal (com les diferències en la freqüència d’aparició de diverses regles) podria facilitar el processament de múltiples sistemes estructurals dins d’un input lingüístic.

ABSTRACT

The extraction of abstract rules from speech is paramount for language acquisition. The present dissertation explores the processing of linguistic rules by studying how our brain discovers the relevant abstract regularities in the signal. In order to tackle this question I followed three lines of research. First I focused on the detection of surface and structural changes of speech rules that I explored using an ERP approach. The objective was to understand the neural responses that are triggered after abstract rule violations in speech. Second, I studied the effects of the phoneme manipulations. The aim was to discover whether the ERP signatures linked to rule learning differ when the target regularity is implemented over consonants or over vowels. That is, I focused on exploring how different phonetic categories might trigger different neural responses to rule violations. And third, I explored the detection of rules from a heterogeneous context studying how abstract rules might be discovered over a noisy signal. Overall, the results we observed suggest that the manipulation of both the phonologic cues and the context of learning modulate the rule extraction process. More specifically, the present dissertation shows that both the task presented to the listeners and the phonemic cues present in the signal affect the selection of relevant sources of information from the speech. Even more, the experiments reported here show that the presence of a clear differentiating cue in the signal (such as the frequency unbalance across rules), might enhance the processing of different rule systems from the speech input.

PREFACE

When I was a child I remember sometimes I tried to decode the conversations between my mother and my grandmother in the phone; they spoke a weird language called Spanish that I did not know yet. Later on, I became a native speaker of Spanish thanks to my years spent in School. However, this first memory left me with the impression that learning a language is a sort of magic; you start knowing nothing and with relatively little instances you can end up understanding a whole conversation, reading poetry or constructing novel sentences that probably you have never heard before. That is the reason why I was interested in the study of how a language was learned, which were the mechanisms that help us to grasp the meaning of a sentence. This involves acquiring knowledge about the target language at many different levels; not only recognizing the individual sounds that compose each element but also the relations that are being set between them. Combining information at these different levels creates, as a result, a general meaning that can solely exist thanks to that unique combination of words. In contrast of what I thought, this process has nothing to do with magic. In fact, language is a complex stimulus that provides an incredible amount of cues and information that our brain readily uses.

However, even if the linguistic signal possesses several cues that provide useful information for speech processing, discovering these cues is not an easy task. Our brain might possess sophisticated mechanisms able to detect and process these cues. Both the linguistic cues and the learning mechanisms playing a role in speech processing have been broadly investigated. A learner needs to extract both token-specific and token-independent information from the speech signal. It has been shown that since very early in life, infants use different learning mechanisms to extract these kinds of knowledge from speech taking advantage of statistical and abstract or symbolic information respectively (Saffran, Aslin & Newport, 1996; Marcus, Vijayan, Bandi Rao & Vishton, 1999). Since language is a complex stimulus that is organized at distinct hierarchical levels, there should be additional factors that guide the learning process by constraining and facilitating the discovery of specific relevant aspects of the input. For instance, Nespor et al. (2003) proposed a division of labor between consonants and vowels according to which while consonants are given more weight during lexical processing, vowels mainly contribute in syntactic processing. Several studies have provided results supporting this division (Toro et al., 2008; Bonatti et al., 2005; Cutler et al., 2000). More general cognitive factors such as attention and memory have also been found to affect language learning (Endress, Nespor, & Mehler, 2009; de Diego-Balaguer, Martinez-Alvarez & Pons, 2016; Toro, Sinnett, & Soto-Faraco, 2005; 2011). Even more, the learner faces the task of language learning using a very noisy input that contains regularities defined over different hierarchical levels. Or, in the case of listeners growing in a bilingual environment, being exposed to inputs instantiating two or more language systems. In the recent years, given the current multilingual situation for a growing number of people from many parts of the globe, it seems essential to add this factor to the equation, and to explore how learners extract relevant information from multiple linguistic systems. Previous results suggest that learners might need additional indexical cues to process multiple linguistic systems (Weiss et al., 2009; Gebhart et al., 2009). However, more research is need on this issue to define the characteristics of this not-so-special learning situation.

In the present dissertation I will focus on the rule learning process. Throughout three studies I will attempt to give a response to the question of how do the brain grasp the relevant abstract rules from speech and detects rule violations. In the first experimental section, I will explore the detection of both surface and structural changes in speech. Then in the following studies I will evaluate the effects of signal and context learning manipulations in the rule detection process. Hence, in the second experimental section, I will evaluate the effects of the phonemic manipulations on the neural responses to rule violations. In the third experimental section, I will study the effects of heterogeneous learning material, hoping to shed some light on how we are able to learn several linguistic rules from a noisy signal.

The current dissertation is organized in five sections. First, I will briefly introduce the main findings relevant to the study of language learning and specifically related to the rule extraction process. In the following three sections I will present the different sets of experiments that I have carried out during the last years exploring the issues related to the detection of relevant rules and their violations. Finally, in the fifth section I will discuss the results we observed throughout our experiments, taking into account how they might fit with previous findings described in the relevant literature. In this dissertation I shed some light on some aspects modulating language rule learning. However, inevitably this dissertation will also raise new questions that might provide an opportunity to undertake new lines for future research.

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1. INTRODUCTION

1.1. Exploring the roots of language learning

Learning a language is one of the most complex tasks that someone has to accomplish during his entire life. It does not only consist of memorizing a series of words. In order to catch the full meaning of a very simple sentence like *you see ghosts*, in addition to retaining the specific meaning of the individual words *you, see*, and *ghosts*; we also need to detect the relations according to which the words within a sentence are organized. For instance, it is important to notice that *you see ghosts* is different from *ghosts see you*. The identification of words implies knowledge of specific acoustic features (in the case of speech) that differentiate one lexical token from another. In contrast, the knowledge of the rules that organize the words implies more abstract schemas such as "affirmative sentences in English follow the SVO (Subject-Verb-Object) word order" or "to construct a past simple tense we add *-ed* to a verb stem (e.g. *you jump, you jumped*)". Thus, we can say that two very important components of learning a language consists of extracting specific words and abstract rules from the speech input.

When an infant acquires a language, he also has to extract this knowledge from speech. This is intriguing given that infants acquire language in an incidental fashion; that is, with no explicit instructions. This apparent ease suggests that infants might possess specialized mechanisms that help them to extract useful information from the speech input. Several studies have been carried out in this field indicating that in effect there are some specialized mechanisms playing a role in language acquisition.

Acquiring words and rules

As it has been mentioned above, we need to extract words from the speech input. However, contrary to what might seem, this task is not straightforward. This is because the speech input is normally presented without any silences between individual words. This means that a learner is presented with inputs such as *shesworkinghard*; without consistent cues signaling the word boundaries. Therefore, in order to identify the individual words that compose a sentence in speech, the listener might use different information. The listener could, for instance, try to predict the likeliness of one syllable to predict the next one; that is to extract the transitional probabilities between the adjacent syllables. This is actually what Saffran, Aslin and Newport (1996) proposed. The transitional probabilities of adjacent sequences of sounds within a word are higher than between two sequences belonging to different words (e.g. in *myfatherisanartist* it is more likely to encounter *fa* with *ther* than to encounter *an* with *ar*). In fact, Saffran and collaborators (1996) demonstrated that 8 months old babies were able to perform this statistical computation on linguistic material. The infants were presented with a nonsense continuous stream like ***bidaku****padoti****golabu****bidaku…* where there were syllable pairs with a transitional probability set to 1.0 (e.g. ***bida***) and pairs with a transitional probability set to 0.33 (e.g. ***ku****pa*). After 2 minutes of listening, infants were able to discriminate between words (transitional probability of 1.0; e.g. ***bida, labu***) and part-words (transitional probability of 0.33; e.g. *ti**go***, ***bu**bi*). With this experiment it was demonstrated that words can be segmented from a continuous speech signal through statistical computations.

The second information that needs to be extracted from the speech input is relative to grammar. For instance, in order to learn the English subject-verb agreement in the instance ***she*** *speak**s** slowly*, the learner should have an abstract open-ended schema in which he could place the specific items to be analyzed. The learner should extract that the form of the verb should agree with the person in the noun phrase and, most important, to apply this schema to other arbitrary instances (e.g. he could apply the schema to other verbs such as *she jumps*, *he dances*). To explore whether young infants could in fact learn token-independent rules, Marcus, Vijayan, Rao and Vishton (1999) familiarized 7 months old babies with three-syllable stimuli following a rule, for instance the ABA rule would create stimuli with the first and the third token repeated (e.g. *gatiga, linali*). Subsequently, infants were presented with new items following the familiarized ABA rule or a novel rule such as ABB (e.g. *wofewo* and *wofefe*). The results suggested that infants were able to discriminate the two rules. Moreover, the fact that the infants were presented during test with novel items that had not appeared during familiarization (in fact, they were composed by different syllables) excluded any possibility that statistical information extracted during familiarization was useful during test. For this reason, the authors concluded that this rule extraction process conformed a different mechanism from the one responsible for statistical learning related to word segmentation. With these findings, it was demonstrated that the ability to segment a speech input and to extract abstract rule information was in effect present since early on. Actually, recent studies showed that even neonates present significant differences in their neural activity suggesting the presence of these abilities. For instance, neonates' brain reacts when presented with nonsense words that violate an abstract rule (Gervain, Macagno, Cogoi, Peña & Mehler, 2008a), and when neonates are presented with a stream of syllables and they detect the word boundaries (Teinonen, Fellman, Näätänen, Alku & Huotilainen, 2009; for similar results in the visual domain see Bulf, Johnson & Valenza, 2011).

To sum up, it is suggested that in the word segmentation process infants extract relations between adjacent syllables to identify specific words. In contrast, in the rule learning process, infants do not rely on the specific phonemes; but they extract an abstract schema and they can generalize this schema to new, never-heard-before phonemes (Marcus, 2000). The possession of these two powerful analytic mechanisms might be in part responsible for the apparent ease with which infants seem to acquire the language. Adults can also be faced with a new language later on in life. There are studies showing that adult learners possess the same analyzing mechanisms as infants, and that they can also perform complex computations crucial for language learning in an incidental manner and to become a proficient speaker (e.g. Peña, Bonatti, Nespor & Mehler, 2002; Saffran, Newport, Aslin, Tunick & Barrueco, 1997; Toro, Sinnett & Soto-Faraco, 2011).

Given the importance that these learning mechanisms have in language acquisition, numerous researchers have explored their supporting neural substrates. In the section below, I will present the main relevant findings in this domain.

Neural signatures of statistical learning

One way to study the neural markers involved in statistical learning is through the Event Related Potentials (ERP) recording while participants do a word segmentation task. The ERPs allow the researchers to observe the time course of the processes that take place during a specific task. Sanders, Newport and Neville (2002) studied the segmentation of nonsense speech streams where words were defined by their statistical regularities (just as in the experiments by Saffran and collaborators, 1996). The authors presented non-segmented streams to the participants and observed that the N100 component was elicited after the onsets of the words. This component was also observed with streams of real English words (Sanders & Neville, 2003) suggesting that the N100 could be elicited by words in a stream containing lexical cues as well as with just phonological and statistical cues. Thus the N100 component was interpreted as a neural correlate of a word's onset detection, reflecting a mechanism involved in speech segmentation.

After the elicitation of the N100 component, Sanders et al. (2002) also observed an N400 component that had been related to word learning and lexical search (e.g. Kutas & Federmeier, 2000; Lau, Phillips, & Poeppel, 2008).Other authors have replicated these results; for instance, Abla, Katahira and Okanoya (2008) observed both the N100 and the N400 after a segmentation task with tone words. Moreover, the authors showed that the N100 and N400 amplitudes were differently elicited in a group of low and high learners. Actually, the N100 and N400 components were elicited only in the group of middle and higher learners, but not in low learners. This result suggested that such neural components are effective markers of detecting and learning novel words. Also, the N400 was elicited only during the early phase of segmentation, so the N400 reflected a first step in learning process. This is what Cunillera et al. (2009) observed during a speech segmentation task; the N400 decreased with a longer exposure. For this reason the authors considered that N400 reflects an early evaluation of possible candidate words during speech segmentation (see also Rossi, Jürgenson, Hanulíková, Telkemeyer, Wartenburger, & Obrig, 2011).

Buiatti, Peña and Dehaene-Lambertz (2009) evaluated the steady-state power response (SSR) labeled by different frequency tags in order to study how the brain might synchronize to the frequency of the statistically-defined words. The authors presented participants with a non-segmented speech stream organized in trisyllabic words that could be randomly ordered, with and without pauses between words. The results showed that the SSRs at the frequencies of one syllable and three syllables were different between conditions. When the streams were randomly ordered, both in the condition with and without pauses, the peaks were found in the frequency of single syllables; suggesting that the processing unit was the syllable. However, when the syllables were presented in the correct order, with statistical regularities defining word sequences, the peak in the frequency corresponding to a single syllable decreased. Instead, the peak corresponding to three syllables increased and reached the significance level when the streams contained pauses (for similar results see Batterink & Paller, 2017). Also, the trisyllabic power correlated with the performance in a word learning test. In the same vein, Batterink and Paller (2017) also found a correlation between the trisyllabic power and posterior behavioral measures of word identification. This suggests that the SSR is modulated by the changes in word perception induced by statistical cues grouping sequences of syllables into words and that such measure of brain synchronization to the word frequency can also predict results in subsequent word recognition tests. Finally, in the study of Buiatti et al. (2009), the trisyllabic frequency presented a greater power in anterior frontal and posterior occipital electrodes. It was suggested that distinct neuronal populations are implicated in the peaks of the different frequencies.

Other studies using functional magnetic resonance imaging (fMRI) provided more accurate information about the possible brain areas involved in word segmentation. Karuza, Newport, Aslin, Starling, Tivarus and Bavelier (2013) showed that the left superior temporal gyrus is more activated when participants are presented with a forward speech stream than when they are presented with a backward speech stream. López-Barroso, Catani, Ripollés, Dell'Acqua, Rodríguez-Fornells and de Diego-Balaguer (2013) observed that word learning was related to functional connectivity between Broca's and Wernicke's areas in the left hemisphere.

Moreover, some areas are specifically related to word segmentation such as left inferior frontal gyrus and subcortical components of the basal ganglia (Karuza et al., 2013).The activation of right posterior cingulated gyrus has been also observed during the first stages of segmentation (Karuza, Li, Weiss, Bulgarelli, Zinszer & Aslin, 2016). In general, it seems that the activation of this area might have a facilitator effect in the segmentation of subsequent speech streams (Cunillera et al., 2009.).

As I mentioned above, a number of behavioral studies have suggested different mechanisms underlying word and rule learning. Following this hypothesis, de Diego-Balaguer, Toro, Rodriguez-Fornells and Bachoud-Lévi (2007) conducted an ERP study to see whether these processes relied as well on different neural mechanisms. The authors presented participants with a subliminally segmented speech that contained trisyllabic pseudowords. Each of them followed a rule where the first syllable determined the last one (e.g. ***pa**li**ku***, ***pa**se**ku***, ***pa**ro**ku***). The aim of the study was to explore the temporal dynamics of two different processes; the memorization of specific words and the generalization of the abstract rules. For this, three different phases were designed. In the learning phase, participants were presented with the artificial language. In the violation phase, participants were presented with a modified stream where non-rule words and non-words where introduced. Finally, in the recognition phase, participants were assessed for word and rule learning. The ERPs recorded during the experiment showed that rule and word violations trigger different neural responses (see Figure 1). The performance in the word learning test correlated with the N400 component. This neural signature coincided with previous studies exploring the recognition of statistically-defined words and closely linked to lexical processes (Cunillera, Toro, Sebastián-Gallés & Rodríguez-Fornells, 2006; McLaughlin, Osterhout & Kim, 2004; Sanders et al., 2002). Alternatively, the rule learning performance correlated with the P2 response. Thus, this study converged with other works observing the lexical N400 related to word learning and added further evidence to the proposal of two separate mechanisms underlying rule and word learning (see also Cheng, Schafer and Riddell, 2014).

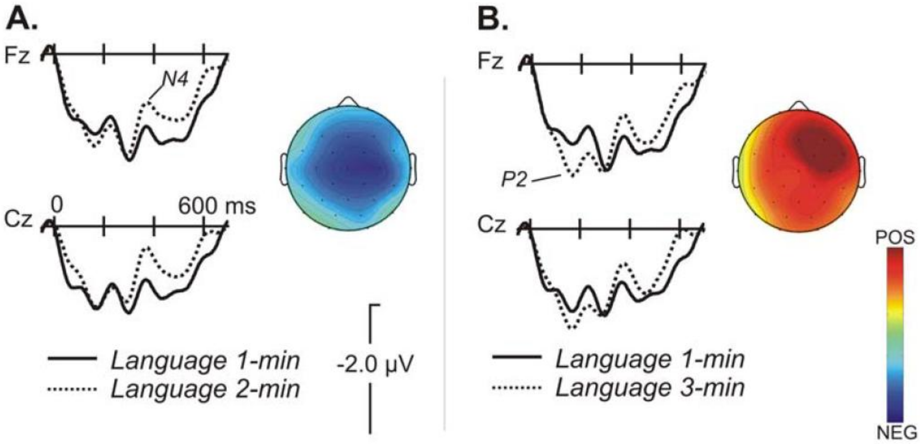

Figure 1. Results from De Diego-Balaguer et al. (2007). A. The comparison of the ERP averages showed an N400 component triggered from the second minute of exposition. B. After 3 minutes of exposition, a P2 component was observed. *Reproduced from De Diego-Balaguer et al. (2007).*

To sum up, the studies devoted to the brain responses during speech segmentation and word learning (as defined by statistical cues) showed that N100 and N400 responses are characteristic in this process. TheN100 is related to the detection of word boundaries in a non-segmented stream while the N400 reflects an early phase of segmentation and has been related to the evaluation of word candidates. Moreover, it is suggested that rule and word learning elicit distinct neural components, adding more evidence to the proposal that these are divergent learning mechanisms. In the section below, I will expose the findings specifically related to rule learning.

Neural signatures of rule learning

In the study from De Diego-Balaguer et al. (2007) the authors observed an N400 for word learning and a P2 after rule learning, thus providing evidence for different electrophysiological responses after these two different tasks. Because P2 has been linked to attention and perceptual learning (Hillyard, Hink, Schwent & Picton, 1973; Reinke, He, Wang & Alain, 2003) de Diego-Balaguer and collaborators proposed that in their experiment, the P2 reflects an attentional recruitment through cues present in the linguistic stimuli. This recruitment of attention could enhance the processing of the structural information of the speech input. A more recent study found similar results. Cheng and collaborators (2014) presented participants with words, pseudowords and non-words. Pseudowords differed with words in a single phoneme and have a high phonotactic probability and non-words were not derived from any word and thus had a low phonotactic probability. The authors found a greater N400 component for words and a greater P2 for non-words, reproducing the results encountered by de Diego-Balaguer and collaborators (2007). In this case, the authors interpreted that the P2 component reflected the processing of the phonological information (see also MacGregor, Pulvermüller, van Casteren & Shtyrov, 2012).

Using a complementary approach, Sun, Hoshi-Shiba, Abla and Okanoya (2012) observed different electrophysiological signatures related to abstract rule learning. The authors presented adult participants with trisyllabic stimuli following either an ABB or an ABA rule (similar to those used by Marcus et al., 1999). Subsequently, participants' rule learning was assessed with new items. Surprisingly, the authors observed a negative deflection around 400 ms after the presentation of the rule inconsistent with the previously learned rule (see Figure 2). This result contrasted with the previous observations from de Diego-Balaguer and collaborators (2007) and with other studies supporting the N400 association with lexical information (Kutas & Federmeier, 2000; Lau et al., 2008). Actually, other authors observed the N400 in tasks related with categorization (Núñez-Peña & Honrubia-Serrano, 2005; Polich, 1985) and grammar processing (Choudhary, Schlesewsky, Roehm & Bornkessel-Schlesewsky, 2009; Mueller, Girgsdies & Friederici, 2008), suggesting that the N400 component might also reflect processing of more abstract regularities in linguistic contexts.

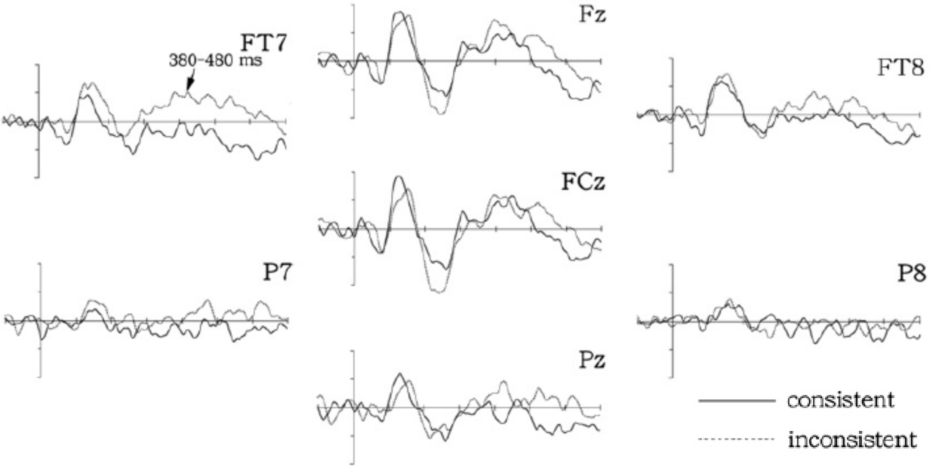

Figure 2. Results from Sun et al. (2012) ERP averages of the High score group. A negative component around 400 ms was observed after the presentation of inconsistent rules. *Reproduced from Sun et al. (2012).*

Similarly, in the study from Tabullo and collaborators (2011) an N400 was triggered after incorrect artificial grammar sequences. However, they also observed a P300 and a late positive component. The authors trained adult participants with an artificial grammar and then they were presented with new grammatically correct and incorrect items. The authors observed a P300 and a N400 after the presentation of the incorrect stimuli followed by a later positivity. The P300 component has been related to the reorientation of attention (Polich, 2007), but it has also been observed after structure violations (that is, after changes in abstract rules; Bekinschtein, Dehaene, Rohaut, Tadel, Cohen & Naccache, 2009). In the study by Tabullo and collaborators, it was the grammatically incorrect words that triggered the P300. The authors interpreted the late positivity they observed in their experiment as the P600 component related to syntactic processing and expectancy violation (Bahlmann, Gunter & Friederici, 2006; Tabullo, Sevilla, Segura, Zanutto & Wainselboim, 2013). Thus, the emerging picture is that the P300 and the P600 reflect similar, complementary, processes related to abstract regularities. However, the P600 might be related to the processing of more complex structures (Christiansen, Conway & Onnis, 2012).

Other studies have used the Oddball paradigm to study the detection of changes in an auditory input. This experimental design consists on presenting two kinds of stimuli. The standard stimuli are highly frequent sequences that are occasionally replaced by deviant stimuli, which are infrequent sequences. Typically, deviant stimuli differ in one or more aspects with standard stimuli. Thus, the switch from the standard to the deviant stimuli can be detected. Such switch triggers ERP components related to change detection (e.g. Mismatch negativity (MMN) and P300). These changes differentiating standard from deviant stimuli can be physical but they can also consist on more abstract, second order, characteristics of the stimuli (e.g. Cornella, Leung, Grimm & Escera, 2012; Mueller, Friederici & Männel, 2012; Paavilainen, Simola, Jaramillo & Näätänen, 2001). Likewise, in the linguistic domain, deviant stimuli can, for instance, contain a grammatical error. Using this experimental design, the MMN component has been observed after grammatical agreement violations (Pulvermüller & Shtyrov, 2003) and after changes in abstract regularities during the presentation of an artificial language (Mueller et al., 2012). This is interesting given that the MMN is elicited as soon as 150 ms after a change onset and it reflects a pre-attentional detection of changes (for a review see

Paavilainen et al., 2001). Thus, this suggests that a grammar error can be rapidly detected. Complementarily, the P300 component reflects a reorientation of attention towards unexpected changes (Escera, Alho, Winkler & Näätänen, 1998). As I mentioned above, the P300 has also been observed after grammatical errors (Tabullo et al., 2011; 2013) and after abstract pattern modifications in a sequence of sounds (Bekinschtein et al., 2009). Emergence of the P300 component under these different conditions suggest that changes in an abstract structure may lead to an engagement of attention.

In summary, it has been demonstrated that rule learning and word segmentation are reflected by distinct ERP signatures. Moreover, several neural components have been associated with the rule learning mechanism. The P2 component has been correlated with the good performance in a rule learning task (Cheng et al., 2014; de Diego-Balaguer et al., 2007). This component reflects an early engagement of attention by linguistic cues present in the signal. The N400 is a family of electrophysiological activations that has been related to processing of lexical information but it might also reflect structural information and abstract rule processing (Sun et al., 2012; Tabullo et al., 2011). Finally, several components related to change detection have been observed after different grammar and rule errors. The MMN reflects the rapid detection of artificial grammar errors (Mueller et al., 2012; Pulvermüller & Shtyrov, 2003), the P300 component has been associated to the processing of abstract information and to attentional switching mechanisms (Bekinschtein et al., 2009; Tabullo et al., 2011), and the P600 reflects the detection of more complex grammatical errors (Christiansen et al., 2012). In the present dissertation, I will take advantage of the aforementioned Oddball paradigm to search for the components signaling the rapid detection of abstract rule errors that has not been explored before. Moreover, I will distinguish between the detection of phoneme, first order, changes and the detection of rule, second order, changes. Following the reviewed literature I expect to find components related to change detection such as the MMN and the P300.

1.2. Constraints and generalities of rule learning

The study of the neural responses that are triggered by the detection of changes in abstract rules in particular and the underlying biological bases of grammar learning in general also opened the door to explore other aspects of the rule learning process. More specifically, to explore the conditions under which abstract rules can be picked from the signal as to be readily learned. As I will explain below, we were especially interested in the neural responses that might support some functional differences that have been observed for distinct phonetic categories in a rule learning task. Complementarily, we were also interested in how the abstract rules might be learned under non-optimal conditions, that is, when they are presented in a signal containing conflicting evidence, as in the case of the oddball paradigm.

The existence of patterns and potential rules is not exclusive of the linguistic input. The extraction of structural information helps us to understand how the world works and allows us to make predictions. In fact, we usually apply simple rules in our daily lives. For instance, the first time we ate a succulent steamy soup we probably ate it and burned our tongue. Then we probably learned that when soup is steamy it burns. And even we could apply this rule to any kind of food. Several authors have studied the extraction of rules in non-linguistic domains. Saffran, Pollack, Seibel and Shkolnik (2007) presented 7 month-old infants with animal pictures following simple visual rules. The results suggested that the infants were able to classify the animal pictures using the rules (e.g. dogs with long tails and dogs with short tails). Dawson and Gerken (2009) showed that 4 month-old infants were able to learn rules from music tones. However, in the same study 7 month-old infants failed at this task. Actually, it has been shown that rule extraction is limited from a variety of non-speech material (Johnson et al., 2009; Marcus, Fernandes & Johnson, 2007).

Thus, these results unveiled the possibility of specific linguistic factors influencing the rule extraction process during language learning. In fact, Ferguson and Lew-Williams (2016) showed that communicative cues might enhance the process of rule extraction from auditory material (although see also Rabagliati, Senghas, Johnson & Marcus, 2012). In a similar vein, another study suggested that linguistic stimuli enhance rule extraction in other domains. Marcus et al. (2007) observed that 7.5 month-old infants extracted rules from non-speech input only when they previously listened to the rules applied to linguistic stimuli. The authors concluded that there might be some cues in language input that facilitate this process. In relation to this proposal, some authors have explored the potential learning cues specifically contained in the linguistic input.

Peña and collaborators (2002) showed that acoustic cues such as subtle pauses introduced in the language stream might help to trigger specific structure-extraction processes. These subliminal cues enhanced rule extraction from the continuous speech stream. The authors found that adult listeners were able to extract statistical information from the speech input when they were presented with unsegmented words. However, listeners could only detect the structural abstract regularities defining the nonsense words once acoustic cues were introduced (putatively, the effect of these acoustic cues were to make the stream more “language-like”). With this experiment the authors demonstrated that signal characteristics affected the computations applied over it. In another experiment, Langus, Marchetto, Bion and Nespor (2012) demonstrated that learners can make use of prosodic cues to extract rules from the speech. The authors superimposed prosodic contours over frequencies of nonsense AxC words and observed that listeners correctly discovered the non-adjacent regularities defining the sequences. In the absence of such acoustic cues, the listeners were able to segment the sequences, but were not able to discover the target non-adjacent regularities. This kind of experiments show that certain cues present in the linguistic input might modulate the kind of structures that might be discovered in the signal.

Besides prosodic information, the speech signal contains other cues that might modulate the regularities that listeners are able to discover. For instance, the phonological representations include the distinction of syllables, consonants and vowels. Different experiments have shown that these complex representations are differentially processed at a neural level since the earliest stages of language acquisition (Dehaene-Lambertz & Dehaene, 1994). For this reason some authors have been interested in the study of the potential influence of these kinds of linguistic representations in the processing of language. In the section below, I will present a variety of studies exploring the possible influence of the phonetic categories in language learning.

1.2.1. An intrinsic constraint: the phonemic specialization

In Semitic languages such as Arabic, consonants signal the word structure corresponding to a lexical meaning and vowels are used to specify the function of the word. For instance, the structure *ktb* corresponds to *write*, and adding some vowels in this lexical root we can construct other related meanings such as *katib* (*writer*), *kataba* (*he wrote*) or *kitab* (*book*). This phonemic specialization was one of the reasons for Nespor, Peña and Mehler (2003) to propose a focus on consonants in the lexical specification of words. Although Semitic languages can be considered as an extreme example of introflection, the opposite pattern has not been encountered in any known language. Moreover, Arabic has 29 consonants and only 3 vowels, and, similarly, across many languages, the quantity of consonants tends to be greater than the quantity of vowels. The higher variety of consonants permits the creation of many different combinations needed in the lexical specifications. In contrast, vowels carry more prosodic information through intonation and stress (Nespor & Vogel, 1986) and have been related to melody and pitch information (Kolinsky, Lidji, Peretz, Besson & Morais, 2009). Being the main carriers of prosody, vowels might provide information about the underlying syntactic structure of language through prosodic bootstrapping (Christophe, Nespor, Guasti, & Van Ooyen, 2003).

These putative differences between consonants and vowels have been summarized in what is known as the Consonant-Vowel hypothesis. This hypothesis exposes that consonants and vowels might play separate roles in language processing (Nespor et al., 2003). The consonant tier might provide lexical cues while the vowel tier might carry prosodic information and, consequently, provide syntactic cues. Coming back to the first section of the present dissertation, a learner needs to extract two main kinds of information from the speech input; words and rules. Thus, some authors studying the functional differences between consonants and vowels have explored if they extend to word segmentation processes and rule extraction tasks respectively.

Behavioral evidence of functional distinctions

Several experiments using different experimental methodologies with both natural and artificial stimuli have demonstrated that consonants and vowels tend to play different rules during language processing. Bonatti, Peña, Nespor and Mehler (2005) presented French speakers with a continuous stream of speech containing transitional probabilities carried by the consonants or the vowels. The authors observed that participants identified words from part-words when the transitional probabilities were carried by consonants. However, they were able to track the transitional probabilities on the vowels only in some circumstances. The results thus suggested that adult learners have difficulties identifying words in a stream having the transitional probabilities carried by vowels. Moreover, it is worth taking into account that this study was carried in a French population and French has 17 consonants and 16 vowels. That is, the functional differences between phonological categories were observed in a language with a good balance between the distribution of consonants and vowels. Using a different experimental task (word reconstruction), Cutler, Sebastián-Gallés, Soler-Vilageliu and van Ooijen, (2000) provided similar results in native speakers of Spanish and Dutch. The authors observed asymmetries in a lexical reconstruction task depending on the phonologic manipulation. Listeners tended to keep the consonant frame over the vowel frame of target words. Therefore these results indicated that the functional division of consonants and vowels goes beyond their relative distribution in a specific language.

A complementary set of experiments explored whether functional differences between consonants and vowels could also be observed in a rule learning task. Toro, Nespor, Mehler and Bonatti (2008a) presented participants with speech input that contained different kinds of information over consonants and over vowels. The transitional probabilities defining nonsense words were carried by one segment and could be used to identify single words, while abstract rule information was carried by the other segment. For instance, in the speech stream presented during Experiment 1 of that study, vowels were disposed following an ABA rule, so the first and the last vowel within a word were the same (e.g. *biduki*, *budiku*), while consonants provide the lexical information through the transitional probabilities (within words the consonants' transitional probability was .7 while between words the consonants' transitional probability was .16). Then, the authors evaluated whether participants could distinguish between rule words and non-rule words, and between words and part-words. The results showed that participants identified single words using the consonants' transitional probabilities and extracted rules using the vowel tier. However, when the roles of consonants and vowels were exchanged, participants were not able to use consonants to extract structural information even when the task was simplified. The authors concluded that phonological information might modulate the kind of regularities that can be extracted from the linguistic input. However, given that vowels carry more energy than consonants (Ladefoged, 2001; 2006; Mehler, Dupoux, Nazzi, & Dehaene-Lambertz, 1996), the acoustical saliency of vowels has been considered having a role in their functional distinction, especially regarding the vowels' role in prosodic aspects. However, Toro, Shukla, Nespor and Endress (2008b) varied the energy of consonants and vowels and still observed their separate functionalities. Thus, the acoustic characterization does not seem to have a role in the functional distinction between consonants and vowels. Moreover, other studies have also found asymmetric functions of consonants and vowels in the visual domain. For instance, Duñabeitia and Carreiras (2011) observed variations in the effect of the relative position priming depending on whether the primes were constructed using consonants or vowels.

Given that adult learners have had an extensive experience with language; it was still unsolved whether these asymmetric functionalities were a result of this language experience (see Keidel, Jenison, Kluender & Seidenberg, 2007). Pons and Toro (2010) conducted an experiment exploring if these separate roles were present since the first stages of language acquisition. The authors presented 11-month-old infants with trisyllabic CVCVCV words following a rule either carried by consonants or by vowels. The results showed that infants were able to extract the rules only when these were carried by vowels. Complementarily, other previous experiments had shown that the asymmetries in word learning tasks were also present at 20 (Havy & Nazzi, 2009; Nazzi, 2005) and at 11 months of age (Hochmann, Benavides-Varela, Nespor & Mehler, 2011). Even 5-month old babies showed differences in the processing of consonants and vowels (Bouchon, Floccia, Fux, Adda-Decker & Nazzi, 2015). Hence, these experiments overall demonstrated that biases in language processing regarding the phonological categories were evident during the first year of life.

To sum up, a variety of studies carried out in adult and infant populations and across different languages showed results supporting the proposal from Nespor et al. (2003; for recent reviews see Nazzi, Poltrock & Von Holzen, 2016; Toro, 2016). These results suggest that consonants and vowels support the processing of different kinds of information and that such differences can be observed at the behavioral level. However, these studies leave still unsolved to what extent these different functional roles are represented at the neural level. In the section below, I will briefly present neural evidence supporting the functional distinction between consonants and vowels.

Neural evidence of functional distinctions

Caramazza, Chialant, Capasso and Miceli (2000) observed that two patients with conduction aphasia evidenced a selective impairment in the production of consonants and vowels related to different brain damage. One of the patients presented problems in the reproduction of consonants while the other patient showed errors affecting vowels. This double dissociation suggested that the production of consonant and vowel information might involve independent neural representations (see also Knobel & Caramazza, 2007; Monaghan & Shillcock, 2003). Moreover, a previous study had shown a similar dissociation affecting the processing of consonants and vowels using intradural electric arrays (Boatman, Hall, Goldstein, Lesser & Gordon, 1997).These findings overall suggest that phonologic categories have a specific representation at a neural level that goes beyond the specific acoustic features.

Some authors have explored how the functional differences between consonants and vowels are represented in the brain by studying the neural activation triggered when a given task is performed over consonants or over vowels. Carreiras and Price (2008) explored if neural activation during a lexical decision task was modulated by whether the target information was carried by consonants or by vowels. The authors used fMRI to study the brain activation when participants read words aloud or when they performed a lexical decision task. They analyzed whether these activations were affected by the type of letter manipulation. The authors observed that consonants and vowels triggered different brain areas activations depending on the task. Specifically, in lexical decision tasks, consonant changes trigger an activity in left hemisphere lexico-semantic areas. In contrast, vowel transpositions affected the processing of prosody and altered the neural activity of left and right hemisphere prosody-related areas. Similar results were observed from analyses using ERPs; different electrophysiological responses were triggered after consonant and vowel transpositions in pseudowords (Carreiras, Vergara & Perea, 2007), in visual word recognition tasks (Vergara-Martínez, Perea, Marín & Carreiras, 2011) and in lexical decision over words and pseudowords with consonants and vowels delays (Carreiras, Gillon-Dowens, Vergara & Perea, 2008).In the latter study, the authors observed distinct ERP responses between consonants and vowels manipulations since as early as 150ms. This result suggested that their functional distinction was processed since an early time window. Moreover, this different neural processing of consonants and vowels seems to be present also since early in life. Benavides-Varela, Hochmann, Macagno, Nespor and Mehler (2012) observed that newborns showed different neural activity related to the processing of consonants and vowels. The babies were first familiarized to disyllabic pseudowords and then they listened the same pseudowords but with consonant or vowel changes. The analysis of the near-infrared spectroscopy (NIRS) showed that the neural activity was greater after a vowel change.

To sum up, studies using a variety of techniques (ERP, NIRS, fMRI) in adults, young infants and even newborns suggest that consonants and vowels not only present different representations in the brain, but also that their functional differences are as well reflected in the neural level. These results add further support to an important number of behavioral studies in babies and adult speakers of a variety of languages suggesting that consonants and vowels can modulate the processing of the speech input (Nazzi et al., 2016; Toro, 2016). Moreover, these studies are also in line with the proposal of a division of labor for consonants and vowels during language learning (Nespor et al., 2003). In the current dissertation, I will explore whether these functional differences lead also to dissociable neural profiles during a rule learning task. More specifically, I will focus on the detection of abstract rule violations using an oddball design. Taking into account the previous literature, I expect to observe that the ERP activity is modulated by the different phonological categories implementing the target regularity.

1.2.2. An extrinsic constraint: the influence of context

Constraints on the operation of rule learning mechanisms seem also to operate at the contextual level. The context of learning or the way stimuli is presented seems to have an influence on the target regularities that a listener can extract from the signal. For instance, there are studies showing that the processing of rules is facilitated when they are presented embedded in tonal melodies in comparison to when they are presented in random melodies (Endress, 2010); or that repetition-based rules are better learned when they are presented at the edge of a sequence than when they are presented in the middle positions (Endress, Scholl & Mehler, 2005). In the same manner, the specific presentation of the speech material might affect language learning. In the course of the present work, we presented participants with a heterogeneous signal in which 90% of the tokens instantiated the target rule (standard words) while the remaining 10% of the tokens instantiated a different rule (deviant words). I was thus also interested in whether this non-homogeneous signal could affect the discovery of the regularities we were targeting in our experiments, and thus decided to more carefully explore this issue.

Hence, the study of the contextual factors, such as the introduction of deviants in an oddball sequence, seems relevant to draw a better picture about the constraints that modulate how we extract abstract regularities from the signal. This is one of the issues that I will explore in the current dissertation. In the following section, I will present previous results exploring language learning when irrelevant stimuli are introduced or when more than one rule can be extracted from the speech input.

Rule learning from heterogeneous input

Some authors have explored the extraction of rules from a heterogeneous context, that is, from an input containing both relevant and irrelevant information. The results showed that, in general, a listener tends to extract a rule from the most relevant or probable stimulus. Gerken (2006) presented 9-month-old infants with a set of trisyllabic words that presented two possibilities of generalization. The author observed that infants tend to extract the most statistically coherent regularity. Romberg and Saffran (2013) presented adult participants with a stream of nonsense words defined over both adjacent and non-adjacent dependencies. They found that the most frequent non-adjacent rule was easier to learn and the participants showed an explicit knowledge of the information they have acquired. Thus, these results suggest that participants were tracking the frequency of presentation of the stimuli and that they might consider the less probable rule as an irrelevant event, or in other words, as an exception.

Some studies have explored the learning of the most relevant regularity from a heterogeneous context varying the ratio of presentation of target and non-target regularities. Gómez and Lakusta (2004) explored the learning of aX and bY patterns presented with ratios from 87/17 to 67/33. The authors showed that 12 month-olds learned the most dominant pattern only in the 87/17 condition, thus suggesting that conflicting evidence might be tolerated up to a certain amount in order to extract the most dominant pattern of the input. Similarly, a study from Gonzales, Gerken and Gómez (2015) observed that 12 month-olds learned the most dominant pattern when it was violated 25% of the time. Moreover, the authors showed that the temporal disposition of the stimuli has an effect in learning. The target regularities were more easily learned when they were presented clustered together than when the target regularities were presented randomly mixed with the non-target regularities. This result suggested that both the ratio and the temporal disposition of the stimuli might modulate the learning of regularities from a conflicting input. Thus, it seems that factors such as ratios of presentation and temporal disposition might modulate the extraction of the most relevant regularity presented in a non-homogeneous context.

However, natural languages are described by several grammatical rules organizing the linguistic structure at different hierarchical levels (e.g. from lexical to syntactical level) and with different frequencies of occurrence (e.g. function words and content words). Hence, a language learner is normally faced with multiple relevant rules acting in different levels. It would thus be expected that participants are able to process different rules at the same time. Actually, in the study by Romberg and Saffran (2013), although participants learned more easily the most frequent rule, they were actually able to extract both adjacent and non-adjacent rules simultaneously presented. Kóvacs and Endress (2014) explored if 7-month-old infants were able to process different abstract regularities at different hierarchical levels. Infants were familiarized to trisyllabic nonsense words containing an adjacent (AAB) or a non-adjacent repetition (ABA) that were embedded in a sentence pattern (ABB). The authors observed that infants were able to track the rules at both levels (the "word" and the "sentence" level), thus demonstrating that 7-month-old infants were sensitive to rules hierarchically organized mirroring the hierarchical organization that can be encountered in natural languages.

Overall, the studies briefly reviewed here suggest that although learners tend to extract the most coherent rule from a heterogeneous input, they can also extract other relevant rules simultaneously. However, there is not enough evidence to be able to establish the conditions under which this learning of multiple rules is possible. In the section below, I will present some studies exploring the learning of multiple regularities from the perspective of bilingual speakers that could help to draw a more accurate picture of how the multiple rule learning works.

Multiple language learning: the case of bilinguals

The processing of multiple sets of rules can be also studied from the point of view of learners in bilingual environments. In these cases the learner is faced with two different rule systems that can be in some cases presented simultaneously. Very few authors have studied this topic. Kovács and Mehler (2009) explored the learning of two different rule systems in 12-month-old infants. The authors presented trisyllabic words following an AAB or an ABA rule to two groups of infants (bilingual and monolingual). The results showed that only the group of infants that were growing in a bilingual environment was able to learn both rules, while the monolingual group learned only the AAB rule. The authors concluded that bilingual infants could be applying a more flexible learning strategy due to their previous exposition to multiple linguistic systems. A bilingual learning environment might act also as an enhancement in the processing of conflicting linguistic input. De Bree, Verharen, Kerkhoff, Doedens and Unsworth (2016) explored the learning of a non-adjacent dependency that was presented together with a 14% of incorrect strings in bilingual and monolingual 24-month-olds. The authors observed that bilingual infants were the ones extracting the target dependencies successfully. Actually, this is in line with other studies showing different learning strategies between monolingual and bilingual speakers during the learning of second labels (Rowe, Jacobson & Saylor, 2015) or in the development path describing the shift on the attention to either the mouth or the eyes of a speaker to take advantage of the redundant audiovisual cues (Pons, Bosch & Lewkowicz, 2015).

Some authors have also studied the complementary question of whether two sets of statistical regularities can be extracted from a heterogeneous signal. That is, there has been an effort to simulate the tracking of statistical regularities across multiple linguistic systems. Weiss, Gerfen and Mitchel (2009) explored the segmentation of bilingual material in monolingual speakers. The authors created two artificial language streams and presented them sequentially to monolingual participants. The results showed that participants were able to track the two linguistic sets only when they were reproduced with two different voices (e.g. a male and a female voice). Similarly, Gebhart, Aslin and Newport (2009) studied the processing of 2 sets of statistical regularities presented sequentially. The results suggested that participants were able to learn the two sets of regularities only when there was a cue clearly separating the two linguistic systems. Thus, the results were in line with the findings of Weiss et al. (2009); suggesting that listeners could segment two linguistic systems only when they were marked by indexical cues. Also, the results might be put in relation to the results provided by Kovács and Mehler (2009), suggesting that monolingual speakers could need extra cues to process two different linguistic systems.

Thus, some experiments have been devoted to the study of learning regularities from different systems (which has been suggested to model the bilingual experience). Results seem to indicate that external factors such as the addition of indexical cues to separate between two sets of regularities could enhance the possibilities of learning contrasting sets of either statistical or abstract regularities. However, the studies tackling this issue are very scarce and much is still to know about the extraction of abstract rules from a signal that does not provide homogeneous information.

1.3. Main goal

The human ability to understand and create novel sentences depends on the extraction and processing of abstract rules according to which a language is organized. Several studies have explored the process of rule learning using different techniques showing some of the conditions that affect the discovery of abstract regularities in speech. In the present dissertation I want to focus on the processing of linguistic rules by studying how our brain discovers the relevant abstract regularities in the signal. That is, I want to shed some light on the brain responses triggered by the processing of token-independent structures, and advance our understanding on the factors that might modulate this process.

To accomplish these goals we carried three sets of studies that will be presented in the different experimental sections. The first experimental section reports a study aimed to understand the neural responses that are triggered after abstract rule violations in speech. Some authors have studied the ERP markers related to rule learning through different experimental designs. These studies have yielded different electrophysiological responses. The P2, P300, P600 and N400 have been observed in grammar learning tasks during artificial language processing (de Diego-Balaguer et al., 2007; Sun et al., 2012; Tabullo et al., 2011).Here we wanted to focus on the brain reactions that are triggered after the detection of unexpected changes in an abstract rule. We thus recorded ERPs when participants were presented with CVCVCV nonsense-words with a frequent rule over the syllables (ABB, example: *feroro*) that sometimes was violated. That is, the rule was replaced by a different infrequent pattern (such as ABA, example: *kiluki*) following an oddball paradigm. With this design, we expected to observe neural responses such as the MMN or the P300 component that are typically triggered after pattern changes (Bekinschtein et al., 2009; Mueller et al., 2012; Pulvermüller & Shtyrov, 2003; Tabullo et al., 2011). Importantly, in order to distinguish between physical, first order, changes and more abstract, second order, rule changes, we modified the classic oddball paradigm and created two different kinds of deviant stimuli (Phoneme deviants and Rule deviants).Phoneme deviants followed the same rule as the Standard frequent stimuli but used new phonemes (ABB; example: *kilulu*). Complementarily, Rule deviants followed a new rule (ABA; example: *kiluki*). By contrasting these two types of deviant stimuli, we were able to evaluate the ERP responses specifically related to rule violations.

The second experimental section reports experiments exploring how different phonetic categories might trigger different neural responses to rule violations. Once we observed which ERP markers were associated to rule violation in an Oddball paradigm, we could extend our research to the specific roles consonants and vowels might play during rule processing. As I have exposed above, much work has been done suggesting that the roles we assign to phonetic categories might constrain the regularities that might be extracted from language (for instance see Bonatti et al., 2005; Cutler et al., 2000; Toro et al., 2008a). Neuroimaging and electrophysiological studies have provided evidence supporting the idea that a division of labor between consonants and vowels generates clear neural signatures. More specifically, they have shown a specialization of consonants during lexical processing (e.g. Carreiras & Price, 2008; Carreiras et al., 2007; 2008; Vergara-Martínez et al., 2011). In contrast, there are no studies that try to describe the different roles of consonants and vowels during rule learning from a neural perspective. Thus, in the second experimental section we wanted to explore the electrophysiological responses related to the extraction of abstract rules when they are implemented over either consonants or vowels. For this, we adapted the experimental design of our first study, and created two distinct rule learning conditions; one with the rules implemented over the consonants (example: ABB rule; *fekeke*) and another with the rules implementer over the vowels (example: ABB rule; *fefufu*). We used an Oddball paradigm to register the neural responses elicited after violations of rules carried by vowels and rules carried by consonants. As in the previous experiment, we also used two types of deviants to disambiguate the neural responses to surface violations from the responses to violations in the abstract pattern. Nespor and collaborators (2003) suggested that vowels are the main carriers of abstract structural information (see also Toro et al., 2008a). Thus, in this study we expected to find different ERP responses after the violations of rules implemented over consonants and vowels.

The third experimental section presents a series of studies motivated by the results observed in the first experiment. In that experiment the data suggested that some of the participants, apart from learning the target standard rule, also actually learned the deviant, infrequent rule that was only presented 10% of the time during the experiment. This puzzled us, and we believed it presented us with an opportunity to explore the learning of abstract linguistic rules under noisy, non-optimal conditions. Thus, our aim in the third set of studies was to explore the effects of a heterogeneous learning material in the rule learning process. We thus designed a series of behavioral experiments in which we presented participants with CVCVCV nonsense words in an Oddball paradigm with two rules implemented on the syllables; ABB was used in the frequent standard stimuli (e.g. *tameme*) and ABA in the infrequent deviant stimuli (e.g. *sulisu*). In these studies we explored the rule learning of both frequent and infrequent patterns, and we compared the learning of rules presented with different relative frequencies of appearance (100%, 90%, 50% and 10%). This design also allowed us to explore whether differences in relative frequency could act as a cue to distinguish among sets of regularities and facilitate the learning of multiple rules.

2. EXPERIMENTAL SECTION I

Monte-Ordoño, J., & Toro, J.M. Early positivity signals changes in an abstract linguistic pattern. *PLoS One*. 2017; 12(7): e0180727.

Monte-Ordoño J, Toro JM. Different ERP profiles for learning rules over consonants and vowels. Neuropsychologia. 2017 Mar;97:104–11. DOI: 10.1016/ j.neuropsychologia.2017.02.014

3. EXPERIMENTAL SECTION II

Monte-Ordoño, J., & Toro, J.M. Different ERP profiles for learning rules over consonants and vowels. *Neuropsychologia*. 2017; 97: 104-111.

Monte-Ordoño J, Toro JM. Early positivity signals changes in an abstract linguistic pattern. PLoS One. 2017 Jul 5;12(7):e0180727. DOI: 10.1371/ journal.pone.0180727

4. EXPERIMENTAL SECTION III

Monte-Ordoño, J., & Toro, J.M. (submitted*)

Differences in relative frequency facilitate learning separate abstract rules

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Monte-Ordoño J, Toro JM. Differences in relative frequency facilitate learning abstract rules. Psychol Res. 2019 Mar 11;83(2):384–94. DOI: 10.1007/s00426-018-1036-1

5. GENERAL DISCUSSION

The main goal of this dissertation was to explore how the brain extracts relevant abstract rules from an auditory input and how it detects their violations. Our aim in the first study was to explore the neural responses triggered by the detection of unexpected surface and structural changes in an abstract rule. In the current dissertation we also wanted to explore some of the factors constraining the detection and learning of abstract rules during language learning. Thus, in the second study we wanted to evaluate whether the different functions that have been described for consonants and vowels (e.g. Bonatti et al., 2005; Cutler et al., 2000; Toro et al., 2008a) modulate how the brain reacts to structural violations. Hence, we studied the neural responses of abstract rule processing when the target rules were implemented over different phonetic categories. Finally, we were interested in the conditions under which an abstract rule can be learned. The aim of the third study was thus to explore rule extraction from a heterogeneous learning context. For this, we focused on the use of differences in relative frequency as a cue to promote learning of multiple rules.

In the section below I will summarize the main findings of the current studies and I will further discuss their results and implications for our knowledge about the mechanisms responsible for the extraction of abstract rules.

5.1. Summary of results and discussion

Study 1: ERP responses to rule violations

Much literature suggests that the ability to process abstract rules is crucial both to acquire and to master a language. The cognitive mechanisms allowing for the detection of abstract structures have been broadly studied suggesting that since very early in life, humans incidentally extract this kind of information from the speech input (Marcus et al., 1999). In the first study of the current dissertation we wanted to explore the neural markers signaling the detection of unexpected changes in abstract rules. To accomplish this goal, we designed an experiment based on the classic Oddball Paradigm. We presented participants with two kinds of nonsense words: standards and deviants. The standard stimuli were highly frequent and followed an ABB rule implemented on their syllables (e.g. *feroro*). The deviant stimuli were infrequent and used novel phonemes; the phoneme deviants followed the same ABB rule as standards (e.g. *kilulu*), whereas the rule deviants followed an ABA rule (e.g. *kiluki*). During the presentation of these stimuli we recorded ERP responses.

We observed a P300 component after the presentation of rule deviants. That is, we observed a positivity around 300 ms after the presentation of tokens implementing a violation of the abstract rule defining standard stimuli. Moreover, the amplitude of the P300 component correlated with the participants' behavioral performance in a rule learning test. This component has been associated with the detection of structural changes in the input (Tabullo et al., 2011;

2013). The current results are in line with this interpretation. The P300 was only triggered after rule deviants (not after phoneme deviants). That is, we only observed this electrophysiological response when the rule of the standards was violated, whereas we did not observe a P300 after the presentation of surface (phoneme) changes characterizing phoneme deviants. The frontal distribution of the positivity we observed corresponds to the P3a subcomponent. The P3a signals a reorientation of the attention to the stimuli (Escera et al., 1998; Polich, 2007). Since, in the current study, participants were asked to watch a silent movie while the auditory stimuli were presented, the emergence of the P3a component suggests that the rule violation promoted a temporal reorientation of the participants' attention to the target deviant stimuli. As I will explain with more details below, such reorientation of attention towards deviant stimuli might support the learning of infrequent rules that we observed in the behavioral experiments described in the third experimental section of the present dissertation.

Further analysis evidenced differences in the elicitation of a later N400 component as a function of behavioral performance in the rule learning test. While the group of learners showed a frontal N400 after the presentation of rule deviants, the group of non-learners showed a parietal N400 after the presentation of phoneme deviants. The different N400 distributions might reflect distinct learning strategies (Rossi, Hartmüller, Vignotto & Obrig, 2013; Silva-Pereyra, Rivera-Gaixola, Aubert, Bosch, Galán & Salazar, 2003). While the parietal N400 has been observed in lexical processing (Kutas & Federmeier, 2000; Lau et al., 2008), lexical search (Rossi et al., 2011) and word learning (de Diego-Balaguer et al., 2007), the frontal N400 has been linked to the processing of abstract linguistic structures (Choudhary et al., 2009; Núñez-Peña & Honrubia-Serrano, 2005) and to the detection of rule and grammar violations (Sun et al., 2012; Tabullo et al., 2011). Thus, the group of participants who displayed successful learning of the rules (“learners”) evidenced electrophysiological responses linked to the discovery of structural regularities. On the contrary, the group of participants who did not learn the rule (“non-learners”) evidenced electrophysiological responses linked to lexical activations. The results thus suggest that learners and non-learners could have applied different learning strategies over the same input, affecting their rule learning performance. Putatively, the focus on lexical over structural cues on non-learners might have prevented them from discovering the abstract recurring patterns implemented over all standard words. Importantly, participants in the current study did not receive any instruction regarding the abstract rules implemented in the stimuli. They were only asked to pay attention to the silent film being presented in parallel to the nonsense words. For this reason, there was flexibility in the kind of information they might have focused on.

Study 2: response modulation by phonetic categories

The consonant-vowel hypothesis (Nespor et al., 2003) claims that there are functional differences for consonants and vowels in language processing. Previous behavioral studies carried with speakers of different languages suggested that consonants tend to be primarily used to extract lexical information from speech while vowels are preferred to extract grammar (e.g. Bonatti et al., 2005; Cutler et al., 2000; Toro et al., 2008a). Recently, the use of techniques such as the ERP or the fMRI have yielded the opportunity to study this kind of processes at the neural level. In our second study, we wanted to shed some light on the effects that different phonetic categories might have on how the brain reacts to the violation of abstract rules. To accomplish this goal we used an experimental design similar to the one used in our first study; we presented to the participants a series of standards, phoneme deviants and rule deviants. However, in this case we defined two conditions. In one the rules were implemented over the consonants (e.g. ABB rule; *fekeke*) and in the other, the rules were implemented over the vowels (e.g. ABB rule; *fefufu*). With this design we were able to observe the neural signatures related to the rules implemented over consonants and over vowels separately.

In both the consonant and the vowel condition, we observed a MMN component after the presentation of all deviant stimuli (rule and phoneme deviants). This component reflects the detection of novel and deviant auditory stimuli (e.g. Escera et al., 1998; Pulvermüller & Shtyrov, 2003). In the current study, all deviants (rule and phoneme deviants) were created using new phoneme combinations. Thus the elicitation of the MMN might reflect the detection of changes at the phoneme level, in line with other studies observing MMN after physical local changes (Bahlmann et al., 2006; Bekinschtein et al. 2009). However, further analyses evidenced differences across conditions in the amplitude of the

MMN component. More specifically, in the consonant condition, the MMN amplitude was greater after phoneme deviants than after rules deviants. Correspondingly, the MMN amplitude after phoneme deviants was greater in the consonant condition than in the vowel condition. This suggested that phoneme changes triggered a stronger response in the consonant condition than in the vowel condition. Such pattern of results resembles what has been found in lexical recognition tasks (see Carreiras et al., 2007; 2008), with greater activation over consonants than over vowels during word recognition. This finding fits well with the claim that consonants play a predominantly lexical role during speech processing. Consequently consonants tend to be given more weight during word recognition than vowels (e.g. Nazzi et al., 2016; Nespor et al., 2003). The current results show that the brain reacts more strongly to changes defining nonsense words (phoneme deviants) when the target information is implemented over consonants than over vowels even if the task given to the participants is not a lexical recognition task. This suggests that functional differences between consonants and vowels that have been observed at the behavioral level might arise from very early stages of neural processing as we observed differences across conditions as soon as 100ms after the deviants presentation.

Moreover, we also observed an N400 component that differed across conditions. When the rule was implemented over the consonants, a posterior N400 was triggered after the phonemic changes defining phoneme deviants. In contrast, in the vowel condition a frontal N400 was elicited after a violation of the abstract rule (rule deviants). This dissociation suggested that although all stimuli implemented the same abstract rule and the same violations were introduced across conditions, the participants processed the stimuli differently depending on whether the target regularities were implemented over the consonants or over the vowels. Previous work suggests that the N400 modulation can result from the involvement of different learning tasks (Rossi et al., 2013; Silva-Pereyra et al., 2003). The pattern of results observed in the current study might be reflecting the application of different strategies depending on the phonetic category over which the regularity is implemented. Emergence of a frontal N400 after rule deviants in the vowel condition might signal the processing and detection of abstract regularities (see our results from the learning group in the previous study and Sun et al., 2012; Tabullo et al., 2011). On the contrary, the N400 after phoneme deviants in the consonant condition might signal the focus on word identification (see our results from the non-learning group in the previous study and de Diego-Balaguer et al., 2007; Rossi et al., 2011). Thus, the current results provide further neural evidence that was lacking to the growing evidence that consonants and vowels possess functional differences in language learning and provide new data about the neural responses that support such differences.

Study 3: relative frequency and multiple rules learning

In the previous experiments using an oddball paradigm we observed a high variability across participants in the behavioral rule learning tests we performed. Such variability posed the interesting question of how abstract linguistic rules are extracted in the context of a non-homogeneous signal. Previous work suggests that the context of learning might affect how regularities are detected in the signal (e.g. Gerken, 2006; Romberg & Saffran, 2013). In the present set of experiments, our aim was thus to evaluate the extraction of abstract rules from a heterogeneous signal. In order to explore this issue, we designed a series of behavioral experiments in which we presented to the participants nonsense words implementing different abstract rules. Importantly, the relative frequency of presentation of the different type of rules was manipulated. Hence, this design allowed us to evaluate the process of rule learning in a noisy context and also to specifically study the influence of relative frequency in this process. It has been found that indexical cues such as a change of the speaker's voice promote the learning of multiple statistical regularities (Gebhart et al., 2009; Weiss et al., 2009). Given that listeners readily detect changes in relative frequency as to distinguish different syntactic categories (Gervain, Nespor, Mazuka, Horie & Mehler, 2008b; Gervain & Werker, 2013; Hochmann, Endress & Mehler, 2010), we explored whether such information could be used as a cue to learn multiple rules.

The results we observed across the different experiments suggested that the introduction of infrequent rules into the speech input did not affect the learning of target, frequent, rules. Even more, the clear differences in relative frequency across the two different types of rules seemed to enhance multiple rule learning. In contrast, when both rules were presented with the same frequency of appearance, the presence of multiple rules did affect the learning of the target rule, hindering learning. Strikingly, such decrease in the performance during test was observed even as the number of tokens implementing the target rule increased threefold. These results suggest that two sets of abstract rules can be learn in parallel as long as there is a cue that readily allows to keep them apart. They also suggest that unbalances in the frequency of appearance of different patterns can be used as the cue differentiating among rules. In fact, previous work devoted to bilingual language acquisition highlights the importance of considering the elements of two different linguistic systems as belonging to different categories. Such separation across sources of information might be one of the keys in the learning of multiple linguistic systems (e.g. Byers-Heinlein, 2014). In the current study, the distinct relative frequencies might have helped the listeners to keep the two rules apart and consequently, might facilitate the learning of both rules.

Differences in relative frequency might help in two different ways to the learning of separate abstract rules. First, differences in relative frequency might be used as a cue to keep apart the two different systems, a requisite that has been shown to be fundamental in order to track different regularities (e.g. Gebhart et al., 2009; Weiss et al., 2009). Second, the presence of infrequent events might help learning the non-target rule through a reorientation of the attention (e.g. Escera et al., 1998). That is, infrequent events could draw attentional resources towards them. Support for this idea comes from the P300 component we observed in our first set of experiments that has been linked to attentional reorientation. This would be in line with the evidence that target events might open "attention windows" promoting the processing of task-irrelevant material (Seitz et al., 2010; Seitz & Watanabe, 2005). Hence, the current results suggest that listeners can profit from relative frequency cues present in a speech signal to disambiguate conflicting material and to eventually extract multiple grammar-like rules.

5.2. Discussion of additional issues

The MMN/P300 dissociation and the stimuli variability

In the study we presented in chapter 3 in the present dissertation (where we compared the neural responses to rule violations over consonants and vowels), we observed a MMN component after the presentation of rule and phoneme deviants when the rules were implemented over the vowels as well as when they were implemented over the consonants. However, in the first study presented in this dissertation (where rules were implemented over syllables), we did not observe a MMN component after rule violations. Instead we observed a P300 component only after the presentation of rule deviants. The P300 is a multi-component elicited when memory and attentional elements are activated. The subcomponent P3a or novelty P300 is elicited with novel non-target stimuli over central and frontal electrodes and is considered as an orienting response, reflecting top-down stimulus evaluation (for a review see Polich, 2007). In contrast, the MMN component is frontally elicited and is considered to signal a pre-attentional or automatic change detection because it has been observed after changes in non-attended stimuli (for a review see Näätänen, Paavilainen, Rinne & Alho, 2007; Paavilainen, 2013). Thus, despite the fact that both MMN and P300 have been associated to change detection there are several distinctions between them.

Bekinschtein et al. (2009) proposed divergent interpretations for the MMN and the P300 components according to which they would signal the detection of regularities at different levels in the signal. The authors studied the processing of sets of sinusoidal tones in a variety of conditions varying the degree of attention and awareness of the participants. The results lead the authors to the conclusion that the MMN might signal the detection of local or physical changes in the stimuli (such as phonemic variations). On the contrary, the P300 could reflect the detection of global changes. That is, changes in the abstract structure of a sequence (such as abstract rule changes e.g. from ABB to ABA; see also Basirat, Dehaene & Dehaene-Lambertz, 2014). The pattern of results we observed across studies fits well with this characterization of neural responses. In the study of rule learning over consonants and vowels, the MMN signaled a phonemic change between standards and deviants (for both rule and phoneme deviants). Deviant stimuli were created using new phonemes that were not used in the standard stimuli, thus it was the novel phonemes, so a local or physical change, what triggered a MMN component across both conditions (vowel and consonant conditions) and for both types of deviants (phoneme and rule deviants). In contrast, in the first study (when the rule was implemented over syllables) the P300 appeared only after rule deviants, and not after phoneme deviants. Thus, in this case it was the abstract rule violation, so a global violation, and not the changes in specific phonemes, what triggered the P300 component.

However, why did we not observe the same neural responses in both studies? One possible explanation could be linked to the differences in stimuli characteristics. When we implemented the rules over syllables, 120 different standard stimuli were presented during the experiment. In contrast, when we implemented the rules over consonants and vowels, only 16 standard stimuli were used. Such differences in the number of standard stimuli used across experiments were due to a limitation imposed by the combination of the composing elements of the nonsense words used in each study (combination of syllables in the first study, and combination of different phonemes in the second). Differences in how variable were the standard words could have had an effect on the MMN/P300 elicitation. First, the amount of repetition of the 16 standard words in the study implementing the rules over the consonants and vowels could have hindered the elicitation of the P300 component. As I mentioned above, the P300 is considered as an orienting response and because of that, its amplitude might decrease with the repetition of the stimuli (Ranganath & Rainer, 2003). Thus, high repetition rates of the 16 standard stimuli might have led to a decrease in the neural response around 300ms. Second, to detect the presentation of a novel element among 16 repeating elements is easier than among 120 repeating elements. Making it difficult to detect novel deviant stimuli might have lead to the emergence of a P300 response instead of a MMN when up to 120 standard words were used. In fact, the P300 is affected by task demands and is specially elicited by difficult tasks, such as when the discrimination between elements (e.g. standards and deviants) is not easy (Katayama & Polich, 1998). In contrast, the MMN reflects an "automatic" mismatch detection that might be modulated by factors facilitating the task. Expertise level has been found to affect the elicitation of the MMN in music (Tervaniemi, Rytkönen, Schrögen, Ilmoniemi & Näätänen, 2001) and language input (Näätänen et al. 1997; Friederici, Steinhauer & Pfeifer, 2002); where only the proficient speakers triggered a MMN after a deviant presentation. Hence, this is in line with the current observations. We observed a MMN on ly in the context of highly repetitive few standard words (when the rule was implemented over consonants and vowels). Complementarily, we observed a P300 in the context of a very variable set of standard words (when the rule was implemented over the syllables) that made it harder to detect deviant stimuli.

The emergence of distinct neural responses

In our second study participants were presented with abstract rules implemented over either the consonants or the vowels in nonsense words. We observed that participants significantly learned the rules in both the consonant and in the vowel condition (as suggested above-chance performance in the behavioral rule learning test that was performed after EEG recording). This contrasts with previous behavioral results showing that rules implemented over consonants are difficult to learn in comparison to the rules implemented over vowels (Toro et al., 2008a; 2008b). However, one explanation of this result might be related to the long time of exposure to the stimuli in the present experiment. In our study the words instantiating the rule were presented during approximately 30 minutes. In contrast, in previous experiments the time of exposure was around 5 minutes. Thus, in our study the duration of presentation was considerably superior to the time used in the work showing behavioral differences between consonants and vowels. This additional time of exposure could have shadowed possible differences across phonetic categories. Importantly, the ERPs registered in the present study allowed us to observe that in effect there was a difference between both the consonant and the vowel conditions in their neural profile. The N400 was elicited after different types of deviant stimuli and with a distinct distribution across conditions. When rules were implemented over the consonants, the N400 was parietally distributed and emerged only after the phoneme deviants. When the rules were implemented over the vowels, the N400 was frontally distributed and emerged only after the rule deviants. The N400 is a complex component that can reflect a lexical evaluation of the stimulus, showing a larger amplitude with possible lexical candidates (e.g. Kutas & Federmeier, 2000; Lau et al., 2008; Rossi et al., 2011; 2013). The N400 has also been observed after syntactically incorrect items, suggesting it reflects structural information processing (e.g. Mueller et al., 2008; Sun et al., 2012; Tabullo et al., 2011). For this reason, we considered that although all the participants learned the rules in the consonant and in the vowel condition, the different N400 profiles we observed suggested that they were focusing on different learning cues. Thus, even if participants were able to learn the rules using both consonant and vowel tiers, their learning strategies were modulated by the specific phonetic category over which the target abstract rule was implemented.

Interestingly, in our first study, in which we presented rules implemented over syllables, the analysis of learners and non-learners also evidenced a difference in the elicitation of the N400. In this case, the participants that correctly learned the rule showed a frontal N400 after rule deviants. In contrast, the participants that did not learn the rule showed a lexical N400 after the presentation of phoneme deviants. These results mirrored the different N400 patterns observed across the consonant and vowel conditions from study 2. However, in study 1 the different neural patterns correlated with level of performance in the rule learning test, and were not linked to any stimuli changes (as in study 2). Thus, different neural responses across learners and non-learners might suggest that listeners were focusing on different aspects of the signal which might have affected their performance in the learning test. One group of listeners might have focused on the recognition of the individual items (as signaled by a lexically-related N400) and thus performed poorly in the rule generalization test. The other group of participants might have focused on the underlying abstract structure of the items (as signaled by the frontally distributed N400) and thus performed well in the test. Our results suggest that the focus on different aspects of the signal might promote the emergence of individual differences in the learning task.

Despite the fact that we cannot directly compare the results found in studies 1 and 2 due to their differences in the stimuli, it might be interesting to compare how such differences might affect the results we observed. While the study using rules implemented over syllables (study 1) suggests that the individual differences could be due to distinct learning strategies, when rules were implemented over consonants or over vowels (study 2), the neural responses were modulated by the phonetic categories. The results from study 1 suggest that the individual differences might at least partially emerge from the focus on different aspects of the signal. Thus it seems that when no learning strategy is prioritized by neither the instructions given to the participants or by specific constraints built in the signal, individual differences might spontaneously emerge. In fact, previous work on the detection of regularities over syllables also identified how participants who learned the target regularity differed from those who did not (e.g. de Diego-Balaguer et al., 2007). In contrast, the signal might also contain specific information that guides listeners towards a target regularity. That seems to be the case in the study 2 of the present dissertation, when the rule was implemented over either consonants or vowels. Under such conditions, it was the phonetic category over which the rule was implemented what modulated the brain responses that were triggered by deviant stimuli. Thus, when there are no specific constraints embedded in the signal, distinct learning strategies could be equally prioritized and this might lead to the emergence of individual differences. These results show the influence of the stimuli features in the language learning and highlight the need to better study the individual variability in this field.

The rule learning bootstrap: how attention builds momentum

In study 3 of the present dissertation, we carried out a variety of behavioral experiments that overall suggested that clear differences in relative frequency allowed the processing and learning of both target and non-target rules. Previous studies have shown that listeners readily track the relative frequency of appearance of different types of nonsense words (e.g. Gervain et al., 2008b; Gervain & Werker, 2013). Even more, participants are able to use this information to discriminate between different syntactic categories (for instance to distinguish between content and function words; e.g. Gervain et al. 2008b; Hochmann et al., 2010). In the current study we took advantage of this ability to track differences in relative frequency to explore the extraction of rules from infrequent and frequent events.

In study 1 and 2 of the present dissertation we used the Oddball paradigm to better understand the neural responses triggered by the violation of abstract rules. In both studies we observed typical electrophysiological responses (the P300 when rules were implemented over syllables and the MMN when rules were implemented over consonants and vowels) that have been associated to change detection. More specifically, when we implemented the rules over syllables and had a very variable set of words instantiating the target rule we observed a P300 component after rule deviants. The P300 has been associated with changes in the attentional focus (Escera et al., 1998; Yago, Escera, Alho & Giard, 2001). This suggests that deviant events might be very efficient in engaging the attention of the participants. Attention mechanisms help the listener to focus on the processing of relevant stimuli and to avoid the processing of irrelevant input. However, in some circumstances irrelevant or secondary events might also be processed. Such switching of attention could have allowed the learning of the infrequent rule.

Studies on perceptual learning might provide interesting insights regarding the processing of non-target information. Seitz et al., (2010) showed that unattended task-irrelevant sounds could be learned when they were presented simultaneous to task-relevant stimuli. Following the model of task-irrelevant perceptual learning, Seitz and Watanabe (2005) proposed that when a target event occurs, this leads to a temporal increase of the attention that enhance the processing of co-occurring events, even if these simultaneous events are irrelevant or subliminally presented. In a similar fashion, in the study 3 of the present dissertation, the temporary engagement of attention triggered by the presentation of deviant stimuli might have allowed the learning of the deviant rule. Interestingly, attention development has recently been proposed to be an important factor during the first steps in language acquisition (de Diego-Balaguer, Martinez-Alvarez & Pons, 2016). The authors reviewed studies suggesting a central role of attention in language development. It is suggested that the time course of the development of endogenous and exogenous attentional mechanisms is related to the development stages of language learning. Thus, attention development might have an early influence during language acquisition by highlighting the relevant information to be extracted from the linguistic signal. This would be in line with our findings showing that attention temporary peaks (in our case produced by the clear differences across rules in terms of relative frequency) allow the processing of deviant stimuli that maybe in other circumstances would have been ignored. In fact, once differences in relative frequency disappeared (Experiment 3 in our third study) participants showed no evidence of learning the rules.

The results provided by study 3 suggest that the presence of a clear differentiating cue (in this case, differences in the distribution of the rules) facilitates the learning of multiple rules, presumably through changes in the focus of attention. However, more research is needed in this domain in order to better understand how the entire rule learning process works in the context of a noisy signal or in the presence of contradictory evidence.

5.3. Future lines of research

The different sets of results presented in this dissertation add to a growing literature studying the intrinsic and extrinsic factors affecting the discovery of abstract linguistic rules. We have approached our initial question studying the brain mechanisms involved in the discovery of abstract rules in the speech signal and how the phonemic distinction and the stimuli distribution are factors that might modulate the rule learning process. At the same time, the current results open the door to further investigations of several issues highlighted in the course of this dissertation.

In study 1 we observed that a group of participants readily learned the target rule while another group of participants did not. The ERP components associated with each group suggested that learners and non-learners might have focused on different aspects of the signal (learners likely focusing on the abstract recurring patterns, while non-learners likely focusing on the individual words). Hence, individual variability in rule learning from speech might be linked to the source of information used to process the speech input. Other factors such as more general cognitive abilities have been also associated to individual variability during speech processing. For instance, auditory discrimination abilities are related to the detection of the morphologically relevant regularities in speech (Mueller et al., 2012). Also, regarding second language learning, it has been demonstrated that individual variability is linked to the efficiency by which a speaker is able to process sounds in his native language (Díaz, Baus, Escera, Costa & Sebastián-Gallés, 2008). However, other factors should be taken into account for the study of individual differences during abstract rule learning, such as the ability to efficiently categorize the different elements composing a sequence (Crespo-Bojorque & Toro, 2016; Marcus et al., 2007; Saffran et al., 2007) or the interpretation of the stimuli in a communicative fashion (Ferguson & Lew-Williams, 2016; Rabagliati et al., 2012), given that these have been shown to affect the rule learning process. Thus, despite the fact that our results shed some light on the possible source of variability in rule learning, more research is needed on this issue to understand how the different factors modulate an individual's performance in a rule learning task. In fact, the better understanding of the relevant factors constraining the detection of abstract linguistic patterns could eventually be helpful for the design of more personalized methods of teaching. Hence, overall these results highlight the importance of taking into account the individual differences in a future line of research.

In study 2 of the present dissertation we explored how neural responses differed depending on whether the target rule was implemented over either consonants or vowels. The results were in line with the claim that consonants and vowels play different roles in speech processing (Nespor et al., 2003). As I have exposed in the course of this dissertation, several studies have investigated these functional differences at the behavioral level (e.g. Bonatti et al., 2005; Cutler et al., 2000; Toro et al., 2008a). Moreover, previous literature suggests that processing of consonants and vowels involve independent neural circuits (Caramazza et al., 2000; Knobel & Caramazza, 2007; Boatman et al., 1997; Monaghan & Shillcock, 2003), an idea that has received further support from several studies that have explored this distinction with fMRI and ERP techniques by using lexical decision tasks (Carreiras & Price, 2008; Carreiras et al., 2007; 2008) and visual recognition tasks (Vergara-Martínez et al., 2011). In study 2 we focused on possible differences at the neural level during the processing of abstract rules. However, in our experiments we focused on adjacent repetition based rules. There are studies showing differences in the processing of adjacent and non-adjacent rules that could be interesting to take into account for future experiments. For instance, Toro et al. (2011) showed that participants in a diverted attention task were able to learn an abstract rule defined over adjacent relations (e.g. AAB) but failed to learn a rule defined over non-adjacent relations (e.g. ABA). In general, results suggest that it is more difficult to learn non-adjacent repetitions than adjacent ones (Endress, Dehaene-Lambertz & Mehler, 2007; Gervain et al., 2008a; Gomez, 2002; Newport & Aslin, 2004). It would thus be interesting to explore whether such behaviorally-observed differences have clear brain correlates in order to track them at the neural level.

Moreover, as I mentioned above, in the second study we used a relatively low number of standard words because of the limitations imposed by implementing the target rules over consonants and vowels. This resulted in a set of standard stimuli with low word variability. This could be another interesting factor to take into account in future research work. Gomez (2002) observed that participants were able to learn non-adjacent dependencies only under contexts of high variability; this is when the predictability of adjacent dependencies was disrupted. In contrast, with low variability in the input, participants tend to learn specific words rather than the underlying patterns. In the current study, we observed a dissociation in the learning strategy of the participants across conditions. In the vowel condition participants focused on the rule extraction whereas in the consonant condition they prioritized the word learning. The change in the preferred source of information was associated to the phonetic category manipulation.

However, it would be interesting to run follow-up experiments using native listeners of languages with a more diverse phonemic repertoire. For example, languages such as French have up to 12 vowels, opening the door for the creation of much diverse stimuli. Running similar experiments with a more variable input would help us to disentangle the relative contribution of phonetic category and stimuli variability.

Finally, the third study of the present dissertation focused on the conditions modulating the learning of multiple abstract rules. We found that participants were able to learn two rules only when clear differences in relative frequency allowed for the differentiation of them. However, one aspect that we did not take into account in our study is the aspect of bilingualism. All the participants included in our experiments were balanced bilingual speakers of Catalan and Spanish. Several studies demonstrate that bilingualism might affect some aspects of speech processing. For instance, bilingualism might modulate the processing of learning second labels (Rowe et al., 2015) or it can affect the focus of attention during the early months when the language is acquired (Pons et al., 2015). Also, relevant to the present issue, there is evidence showing differences between monolingual and bilingual infants in the learning of multiple rules (Kovács & Mehler, 2009). Some authors have explored the segmentation process from multiple regularities showing that monolingual speakers have difficulties segmenting multiple language systems in the absence of indexical cues (Gebhart et al., 2009; Weiss et al., 2009). Hence, it would be interesting to replicate our study exploring rule learning from an heterogeneous signal with a monolingual population. It could be the case that a monolingual population might find it more difficult to keep the two sets of rules apart. On the contrary, differences in relative frequency might be such a strong cue, as suggested by several authors (e.g. Gervain et al., 2008b; Gervain & Werker, 2013; Hochmann et al., 2010), that even monolinguals are able to learn the two rules in parallel. In the same manner, the studies 1 and 2 were conducted with bilingual population. Interestingly enough, we found a modulation of the N400 component in both studies. The N400 is a late response that reflects top-down cognitive processing. Given that bilingual speakers might display some differences in executive functions when compared with monolingual peers (for a review see Costa & Sebastián-Gallés, 2014), it could be interesting to explore whether the same pattern of negativity responses around 400ms is observed with monolinguals.

6. SUMMARY AND CONCLUSIONS

Several conclusions can be reached from the results observed in the course of the current dissertation. In the first study, implementing rules over syllables, we explored how the brain detects surface and structural changes in an abstract rule. We found that:

- Structural changes in an abstract rule trigger a P300 component that correlates with rule learning.
- In the group of learners, a frontal N400 was triggered after the structural change; whereas in the group of non-learners, a parietal N400 was triggered after the phonemic change.
- The modulation of N400 suggests distinct learning strategies might underlie individual differences in the detection of abstract rules.

In the second study, implementing rules over distinct phonetic categories, we evaluated the different neural signatures of rule learning from consonants and vowels. We observed that:

- After phonemic changes, a MMN component was triggered in both the consonant and the vowel condition, reflectingthe detection of a local change.
- The greatest amplitude of MMN was triggered after phoneme deviants in the Consonant condition. This result is in line with the claim that consonants are given more weight during word recognition than vowels.
- In the Consonant condition, a parietal N400 was triggered after phoneme deviants. In the Vowel condition, a frontal

N400 was triggered after rule deviants. These results suggest different processes were carried in each condition.

- The N400 modulation and the differences in the MMN effect suggests that consonants and vowels possess different roles in language learning, specifically during rule learning.

In the third study, that included a set of behavioral experiments implementing rules over the syllables, we studied the process of rule learning from an heterogeneous input. We found that:

- Listeners are able to extract a frequent abstract rule from an homogeneous signal as well as from incoherent input.
- Remarkably, listeners are able to learn a very infrequent rule that is only presented 10% of time.
- When the frequency of presentation of two rules is balanced, listeners failed to extract an abstract rule.
- The results suggest that the frequency unbalance might be used as a cue to process distinct rules separately and to eventually learn them.
- It is suggested that the unexpectancy of deviants might temporally engage the participants' attention allowing the process of rules poorly represented on the signal.

Hence, different cues present in the input modulate the paramount task of finding relevant information in the linguistic signal. First, both the task presented to the listeners and the phonemic cues present in the signal affect the selection of relevant sources of information from the speech. And second, the presence of a clear differentiating cue in the signal (such as the frequency unbalance present across rules) might enhance the processing of different rule systems from the speech input.

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