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*Cues to lexical stress assignment in reading
Italian: a large-scale investigation of
polysyllabic nonwords*

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Life in an unpredictable journey. I started my university career without a purpose. Over the years I have learned to ask myself questions about who I am and who I want to be. I took the decision to study linguistics, as it was the subject that sparked my interest the most. And so it was that I found out the existence of the psycholinguistics field of studies, which has me fascinated and passionate from the first lesson. I owe a special thank to my thesis supervisor, the professor Lucia Colombo of the Psychology department at University of Padua. She has been the professor of the first psycholinguistic course I took in my first semester of Linguistics and it is thanks to her that I met and appreciated this subject. After one year I asked her to be my supervisor and she accepted my proposal. From that moment she guided me step by step in this work and I could always count on her. Another fundamental part of this work has been the expert Giacomo Spinelli, from the department of Psychology of the University of Western Ontario. His valuable contribution has made our investigation possible and successfully conducted. To him as well goes a proper thank. I would also like to express my gratitude to all the professors of the second cycle degree in Linguistics for their constant support and great competence. I really appreciated everything you have done for me and my career!

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Introduction

The interest on lexical stress assignment process has been increasing in the field of reading research over the past 30 years. The issue has emerged quite recently, because for a long time reading researchers have focused exclusively on monosyllabic units of analysis. Since the syllable which composes a monosyllabic unit is one, establishing which is the most prominent syllable assigning lexical stress was not considered a problematic issue. However, from the last years of the last century researchers have started to investigate and use the polysyllabic units in their analyses. They noticed that polysyllables constitute a great majority within the lexicon of many languages and, therefore, a complete understanding of the reading process requires an account of both monosyllables and polysyllables processing. The processing of polysyllables introduced a new issue in the reading research, which is lexical stress assignment. Assigning lexical stress to a polysyllabic word in reading means to detect the most prominent syllable in the word. This can be recognized in the spoken word by the increased loudness, the vowel lengthening and the changes in pitch. It is assumed that the human beings are provided with a phonological lexicon, learnt and developed with the experience, and that they make reference to it in deciding which is the tonic syllable. In some languages, so called fixed stress languages (e. g. French), the position of lexical stress is the same for every word in the lexicon. On the contrary, in most other languages, the so called free stress languages, the position of the stress varies. Therefore, when readers are presented with a polysyllabic word, they have to establish the correct stress placement before they can articulate and pronounce it. Hence, researchers addressing the reading process have to assess the more specific process of lexical stress assignment in free stress languages. Regarding this topic, the languages mainly taken into account to date in the psycholinguistic literature are Italian, English and Russian.

In the present work, the attention will be mainly focused on Italian. Italian is transparent at the segmental level and opaque at the suprasegmental level. This means that the correspondence between the orthography and the phonology of the Italian words is almost perfect, but the Italian stress system is much more complicated. Indeed, the position of the lexical stress is neither predictable by determined rules nor marked by orthographic signs, such as diacritics. Few exceptions exist but refer to a little portion of the Italian lexicon. Therefore, the readers cannot establish a priori the position of lexical

stress and have to rely on lexical and nonlexical sources of information when they are asked to read isolated polysyllabic units. Which cues to lexical stress are relevant and their relative contribution in the lexical stress assignment process is still a matter of debate and investigations in the field of reading researches. Among the proposals that reading researchers have put forward, the main cues to lexical stress are word knowledge, stress dominance and stress neighbourhood. However, other sources of information might play a role to some extent. For instance, researchers have started to investigate the role of the grammatical category, the syllabic structure, the length of the stimuli in letters or syllables, some morphological units, such as prefixes and suffixes, or some orthographic and phonological units, such as word endings and word beginnings of different length.

From a different perspective, scientists have implemented computational models of reading aloud, which are computer programs created to simulate the human reading process. When the computational models have to process polysyllabic units in free stress languages, lexical stress assignment becomes a problematic issue. Assessing which cues guide the readers in lexical stress assignment may help the scientists to improve their computational models performances. Recently, Perry, Ziegler and Zorzi (2014) have implemented the most functional comprehensive model for Italian to date, the so called Connectionist Dual-Processing model (CDP++). The model has been successful in simulating the reading aloud processing of polysyllabic words from the Italian lexicon. However, the model still presents some limitations.

The present research aims to investigate the factors that influence stress assignment while reading aloud isolated nonwords by means of a large-scale dataset of human pronunciations of polysyllabic nonwords. Nonwords are strings of letters which respect the phonemic constraints of the language, are created to be similar to real words, but without any associated meaning. Since the readers have never read these new word before, they are particularly important for investigating the nonlexical cues to stress.

We have followed determined criteria to build our corpus of nonwords, because we wanted to observe the effect of specific cues and we wanted our corpus to reflect as much as possible the Italian lexicon. Once we created the corpus of 800 nonwords with three, four and five syllables, we tested it on 45 subjects, for a total of 36000 response data. One of the aims is to compare the human data against the Italian CDP++ model

performance on the same task. This will allow us to investigate the functioning of the model and its ability to simulate the process of reading aloud single nonwords and assigning lexical stress to these units and the factors the model relies on while establishing the lexical stress position.

In Chapter 1, after a long introduction in which all the topics related to the process under discussion will be described, the most relevant studies and findings regarding stress assignment in Italian, English and Russian will be presented and discussed. Two megastudies already present in the literature, one on Russian (Jouvralev and Luper, 2015), and one on English (Mousikou, Sadat, Lucas and Rastle, 2017) will serve as reference to the present investigation, and their effectiveness in the investigation of the cues to lexical stress assignment will be illustrated and discussed.

In Chapter 2, the most important computational models proposed to simulate the process of reading aloud single units to date will be presented and discussed. The models will regard in particular the simulation of English and Italian reading. The historical background in which the computational approach emerged and, especially, the two theories which contributed to create the computational models structures will be illustrated: connectionism and dual-route theories. The first set of models includes the computational models implemented to process exclusively monosyllabic units. The most recent versions of the second set, instead, includes the processing of polysyllabic units. A recently proposed approach in the field of studies concerning stress assignment and reading will also be described: the Bayesian approach. This approach has been tested for Russian, but can be adapted to the other languages.

In Chapter 3, a large-scale investigation of the factors influencing lexical stress assignment in reading Italian will be presented. The materials, design and procedure we used for the experiment will be described and the results of the analyses will be discussed. In addition, the performance of the CDP++ computational model by Perry et al. (2014) will be presented. Thus, the human's and the model performances will be compared. The aim of the two experiments is first of all to assess which cues are playing a role in the process and their relative importance in the human performance. Secondly, we aim to test and evaluate the model functioning and its ability to simulate the process under investigation. This involves also to determine which linguistic-distributional cues the model relies on in assigning lexical stress and whether it relies on

the same cues the human subjects rely on. Besides, we provide the research of a large size corpus of nonword stimuli and of a large size nonwords pronunciation dataset that may be used not only in future researches addressing the reading process, but also by scientists in their attempts to create the most effective computational model of reading aloud polysyllabic units, or in the fields of literacy education and reading disorders treatment.

Chapter 1. The process of stress assignment in reading aloud single words

Reading aloud single words is, for skilled readers, a simple automatic task. It starts with the perceptual analysis of a given string of letters and ends with its correct pronunciation, even if the reader has never seen that string of letters before. In practice, this task seems easy to accomplish, but the cognitive mechanisms underlying it are rather complex and include, among others, recognizing visually presented words, deriving a phonological representation of the letter string and articulating it. For several reasons, among which the fact that the variables to investigate can be isolated more easily, than, for example, in reading sentences or prose, the process of reading aloud single words is one of the most studied issues in the area of cognitive science.

Reading researchers started their investigations examining first the simplest units, such as monosyllables. However, in order to achieve a more complete understanding of the reading process, they considered that introducing in their analysis more complex units, such as polysyllables was essential, since polysyllables represent the biggest portion of the lexicon of almost all the existing languages. For instance, according to the Phonitalia database (Goslin, Galluzzi & Romani, 2014) the portion of monosyllables in Italian only represents 1.26% in types and 34.23% in tokens. These percentages are similar in other languages like English, German and Dutch, in which, according to the CELEX database (Baayen, Piepenbrock & van Rijn, 1993), the portion of polysyllables greatly overcomes the portion of monosyllables. The introduction of polysyllables in the reading research led to the investigation of additional issues, as interesting as problematic, among which lexical stress assignment. Other emerging aspects are, for instance, all the problematic issues involving syllables and syllabification, the relationship between segmental and suprasegmental levels and the phonological phenomenon of vowel reduction¹, which, however, will not be considered in the present study.

In this chapter, only the studies regarding exclusively the lexical stress assignment process in reading aloud single polysyllabic words and nonwords will be presented. First, the concepts of lexical stress and lexical stress assignment will be clarified and

¹ Vowel reduction does not appear in the process of reading Italian.

defined precisely. Moreover, a description of how and why the interest on the cognitive process of lexical stress assignment has increased from the last years of the last century will be offered. Among appealing factors and effects regarding the studies on stress assignment in reading aloud, relevant lexical and nonlexical cues to determine the correct lexical stress position will be taken into account: word knowledge, language-specific dominant stress pattern, the stress neighbourhood, certain orthographic correlates of phonological distinctions, such as word endings and word beginnings, the stimulus' syllabic structure, the grammatical category, the morphemic units and the orthographic or phonological similarity to real words.

In the second part of the chapter, all the current studies and investigations regarding lexical stress assignment will be presented and discussed. The discussion will be focused exclusively on three languages: Italian, English and Russian. These languages have been chosen because of their common fundamental characteristic: they are all free-stress languages, which means that position of lexical stress is not predictable. Moreover, to date, a large number of studies and investigations have been proposed with the aim of investigating lexical stress assignment, since they are all appealing for researchers addressing this process. Hence, a complete understanding of this specific mechanism in free-stress languages contributes to achieve the complete understanding of the more general reading process.

The last part of the chapter will be dedicated to the description of a new tool to conduce the experimental investigation on lexical stress assignment, the so called megastudies. By means of megastudies, researchers can conduce experimental and behavioural analysis, both on a larger number of subjects and with a larger number of stimuli; in this manner they can get a wider range of data for their analysis and more reliable results. Moreover, all the orthographic, phonological, morphological and syntactic cues to stress can be examined and evaluated in the task of reading aloud polysyllabic units. In this manner, researchers can establish both the individual and the combined influence of the several cues taken into account in the mechanism of lexical stress assignment to polysyllabic units. Hence, we will consider how this new approach can open the possibility to improve the current knowledge regarding the reading process and develop more and more efficient computational models of reading aloud.

1.1 Stress assignment: studies and insights

In phonology, lexical stress, or word stress, represents the suprasegmental information about a word, which specifies the tonic syllable, the acoustically most prominent syllable in the word. This is processed through different acoustic characteristics: its increased loudness, the vowel lengthening and the changes in pitch. In Italian, for example the tonic syllable is pronounced in a more marked manner than the other unstressed syllables and is characterized by a longer duration (Bertinetto, 1981; Landi & Savy, 1996; McCrary, 2003; Bertinetto and Loporcaro, 2005). In other languages, lexical stress can be identified in more than one level and, therefore, within a given word both a primary and a secondary stress can be found. Other languages present fixed levels of stress (e. g. French and Mandarin). Researchers have demonstrated the important role that lexical stress plays both in the cognitive processes involved in speech perception and segmentation and in spoken word recognition (Cutler & Norris, 1988; Norris, McQueen, & Cutler, 1995; Mens & Povel, 1986; Pitt & Samuel, 1990; Cutler & Clifton, 1984; van Donselaar, Koster, & Cutler, 2005), and in the cognitive processes involved in reading (Kuhn & Stahl, 2003; Whalley & Hansen, 2006; Ashby & Clifton, 2005; Breen & Clifton, 2011).

The reading literature has been mainly aimed at explaining the effects of potentially important variables, such as the frequency effect, according to which high frequency words are read aloud faster and more accurately than low frequency words (Colombo, 1992; Weekes, 1997; Jared, 2002). A second most studied factor is the lexicality effect, according to which the words are read faster and more accurately than nonwords (McCann and Besner, 1987; Colombo, 1992; Weekes, 1997). Third, the regularity effect, according to which regular words are read faster and more accurately than irregular words, and its interaction with frequency, since the regularity effect only occurs for low frequency words (Colombo 1992; Paap and Noel, 1991). Length in letters is also an important factor: the longer the word the higher the naming latencies and the probability of an inaccurate response (Ans, Carbonnel, & Valdois, 1998; Weekes, 1997). Sixth, the interaction of the two effects (regularity and length effects) with the lexicality. Words have latencies and accuracy advantages compare to nonwords. However, regular and smaller words have are pronounced faster and more accurately than irregular and longer words (Weekes, 1997; Ziegler et al., 2000). An

additional factor is the orthographic neighbourhood effect, according to which the greater the number or the proportion of the word body neighbours, the faster and more accurate the response (Ziegler et al., 2001). In Coltheart, Davelaar, Jonasson, and Besner's (1977) definition, body neighbours are words that share all the letters apart from one with the target word. The consistency effect, according to which word with a great number of friends and only a small number of enemies are read aloud faster and more accurately than words with few friends (Glushko, 1979; Seidenberg, Waters, Barnes, and Tanenhaus, 1984; Parkin, 1985). And lastly, the position of irregularity effect is also important: words with the irregularity on the first part of the word are read faster and more accurately than words with the irregularity on the last positions (Rastle and Coltheart, 1999). However, it is worth noting that some of the effects can be found in some languages and not in others, whereas others are more general. Regarding the investigation of lexical stress placement while reading aloud single units, researchers are trying to explain in particular the *stress neighbourhood effect*, in terms of the number of words which share both the same orthographic ending, including the nucleus of the penultimate syllable and the whole ultimate syllable, and the stress pattern with a given word. Also investigated is the influence of the distributional characteristics of stress in a language: in some languages there is dominant stress pattern (much more frequent than others). This has led to the investigation of the dominance effect, according to which the readers develop a bias in favour of the stress pattern which occurs most frequently within the language.

To date, there is strong agreement among researchers regarding the assumption that two mechanisms are working in the reading process (Seidenberg, 2012). Thus, from the printed representation of the stimulus to the correct pronunciation, the cognitive system follows two independent pathways: the two lexical route and nonlexical route. The lexical route is assumed to work through a looking-up of the mental lexicon and, therefore, processes the entire word as a unit. However, the lexical access mechanism is fast and accurate only when the stimulus is an already-known word. Moreover, it was demonstrated to be more effective when the word is highly frequent (Colombo, 1992; Weekes, 1997; Jared, 2002). Low-frequency words, instead, do not get easily activated through the lexical mechanism and, therefore, in the processing of these items the nonlexical route plays a more important role. The results of the two routes can be

congruent or incongruent and in the latter case the pronunciation of the stimulus requires more time to decide between the two responses. At the very beginning, scientists were divided in two fields regarding the way the nonlexical mechanism works. A first trend supported the idea of a rule-based mechanism. However, the results of subsequent empirical studies and researches have failed to provide evidence for a rule-based mechanism and supported, instead, a second trend of opinion, the statistical learning approach (Arciuli, 2018). The statistical learning approach assumed that the process of lexical stress assignment is carried out in a statistic-distributional way in all the existing languages; this means that the reader's cognitive system calculates the correct position of the lexical stress basing on implicitly learned statistical properties involving the relationship some units present in the stimulus and certain stress patterns.

In the next paragraphs, the main empirical investigations will be presented. The discussion will regard three main languages: Italian, English and Russian. These languages are especially appealing for this field of studies, because they have in common the characteristic of being free stress languages. Moreover, all these languages are highly opaque at the suprasegmental level, which means that the position of lexical stress is rarely, or never, neither predictable by rules nor orthographically marked and, therefore, the issue of lexical stress assignment is particularly problematic. Researchers are trying to establish which sources of information the readers rely on in order to establish the correct position of lexical stress, especially when they are presented with low-frequency words and nonwords.

1.1.1 Italian

Italian is a free stress language and most of the Italian words are polysyllabic. Indeed, according to the Phonitalia database (Goslin, Galluzzi & Romani, 2013), the portion of monosyllables within the lexicon represents only 1.26% and the remaining part is composed by words with more than one syllable. Italian polysyllabic words can exhibit four kinds of stress patterns, which are classified starting from the last syllable backward: the ultimate syllable stress pattern, which in Italian is called 'tronco' (e.g. ColiBRi 'hummingbird'), the penultimate syllable stress pattern, which in Italian is called 'piano' (e.g. piSTOla 'gun'), the antepenultimate syllable stress pattern, which in Italian is called 'sdrucchiolo' (e.g. TAvolo 'table'), and the rare fourth-from-last syllable

stress pattern, which in Italian is called ‘bisdrucchiolo’ (e.g. *Abitano* ‘they live’). The distribution of these four stress patterns is asymmetric in the lexicon. Considering disyllabic words, the penultimate syllable stress pattern is nearly the only one, in fact disyllables are almost always stressed on the penultimate syllable. Instead, considering words with more than two syllables, the available data show that in Italian the dominant stress pattern is the penultimate syllable stress. Indeed about 80% of Italian words are stressed on the penultimate syllable and only 18% are stressed on the antepenultimate syllable; the remaining 2% involves words with other irrelevant stress patterns (Thornton, Icobini and Burani, 1997).

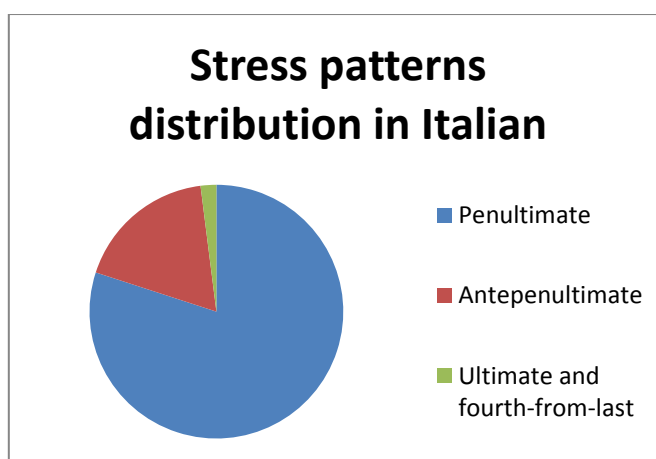


Figure 1. Distribution of the alternative stress patterns in Italian.

Moreover, Italian language is highly transparent at the segmental level, which means that the correspondence between graphemes and phonemes is almost perfect. Alternatively, it is highly opaque at the suprasegmental level. Since it is a free stress language, the position of the lexical stress is not the same for every word and this information is neither predictable by rules nor orthographically marked. However, some exceptions exist. First, when lexical stress is placed on the word’s last syllable, it is orthographically marked by a diacritic (e.g. *colibrì* ‘hummingbird’). However, the proportion of words with ultimate syllable stress pattern is very limited. Second, in Italian a phonological rule that predicts stress position exists and refers to the syllabic structure, in particular to the syllable weight: when the word’s penultimate syllable is heavy, or closes, that is, it ends in a consonant, it mostly bears lexical stress. However, two words do not follow this rule: the words *MANDorla* ‘almond’ and *FINferli*

‘chanterelles’ receive antepenultimate stress pattern, even though their penultimate syllable ends in consonant. Despite these two exceptions, in most cases the lexical stress position within Italian words is unpredictable.²

Lexical stress assignment in Italian polysyllabic words while reading is a process that has been largely investigated over the past 30 years and, to date, some proposals have been put forward. In her seminal study, Colombo (1992) laid the foundations for this investigation. The author proposed as a first source of lexical stress information the word knowledge. When the subjects are presented with printed word stimuli, they can access all the information regarding their correct articulation and pronunciation by means of the lexical pathway. Through a looking up process to the mental lexicon, the cognitive system can retrieve in the memory all the information associated to the target word entry, including the correct position of lexical stress.

In Italian, stress patterns are asymmetrically distributed in the lexicon and the most frequent one is the penultimate stress pattern. This stress pattern is considered the dominant one among the others and, consequently, the regular one. However, Colombo (1992) investigated the role of the implicit knowledge of the predominant distribution of the penultimate syllable stress in a reading aloud naming task, with high and low-frequency words. She found that responses were faster and more accurate for words with the dominant stress, but only when the words were of low frequency. In other terms, the dominance effect only held for low frequency words. This happened because high-frequency words stored in the subject’s mental lexicon get easily activated. Thus, the lexical pathway produces the correct response in processing these items quickly and there is no influence of the distributional characteristics of stress. Low-frequency words are stored in the mental lexicon as well, but their lexical activation is slower. According to the dual route model (Perry, Ziegler and Zorzi, 2010; 2014), while processing these items, both the lexical and nonlexical routes are working simultaneously and the choice between the two competing results produces a delay in the response. Thus, the effect of the distributional characteristics of stress in the language are able to influence the naming latencies.

Hence, when considering the processing of low-frequency words, Colombo (1992) proposed the distribution of the different stress patterns as one of the mainly effective

² For more detailed information, see Krämer, M. (2009). *The phonology of Italian*. Oxford: Oxford University Press. Pp. 156-197.

nonlexical source of information. While the processing of high-frequency words is easily accomplished by the lexical route through a lexical access mechanism, the processing of low-frequency words also requires some reliable nonlexical sources of information and the processing of nonwords is based exclusively on nonlexical sources of information. According to Colombo (1992), while improving their reading skills, Italian readers implicitly learn to distinguish which stress pattern is the most frequent among the others and develop a bias toward it. As a consequence, they tend to assign the dominant stress pattern by default when presented to low-frequency words. Besides this distributional information, Colombo (1992) proposed another nonlexical source of information reliable in reading low-frequency words, which can be found in the stimulus orthography: the word's final sequence. The final sequence of a word, also known as word ending, in Colombo's definition includes the nucleus of the penultimate syllable and the whole last syllable. All the words within a language which share the same final sequence are called neighbours. For instance, in Italian all the words ending with the final sequence *-ola*, like *BAmbola* (doll), *TOmbola* (bingo), *piSTOla* (gun), *COstola* (rib) and *spaGNOLA* (spanish girl) are orthographic neighbours and they all together form an orthographic-phonological neighbourhood. However, within a certain neighbourhood different stress patterns can exist. The words that share both the same orthographic and phonological final sequence and the stress pattern belong to the same stress neighbourhood. All the words of a language belonging to the same stress neighbourhood are called stress friends; for example, in Italian, the words *BAmbola* (doll), *TOmbola* (bingo) and *COstola* (rib) are stress friends, while the words *piSTOla* (gun) and *spaGNOLA* (spanish girl) which share the orthography of the ending, but not the stress pattern, are stress enemies. Thus, all the words that share the same final sequence, but exhibit different stress patterns are stress enemies; for example, in Italian, the words *BAmbola* (doll) and *piSTOla* (gun) are stress enemies. Within a neighbourhood stress friends and stress enemies can be distributed in different or balanced proportions. The larger the number of stress friends to a word in a certain stress neighbourhood, the more that stress neighbourhood is consistent. Alternatively, if a word has many enemies, the stress neighbourhood is inconsistent with its neighbourhood. The notion of neighbourhood consistency has been investigated in monosyllabic word reading in English (Jared, McRae, & Seidenberg, 1990; Plaut,

McClelland, Seidenberg, & Patterson, 1996; Kelly, Morris, & Verrechia, 1998; Jared, 1997, 2002; Monaghan & Ellis, 2002) in relation to the regularity of the orthography-phonology correspondence showing processing advantages when the words stimuli belonged to a highly consistent neighbourhood.

Colombo (1992) used the idea of consistency not in the same domain (Italian is very regular in the grapheme-to-phoneme correspondence), but referring to stress. Hence, Colombo (1992) proposed different levels of stress predictors. At a general level, she proposed word knowledge, whereas, at a more specific level she proposed stress dominance and orthographic word endings, related to stress neighbourhood. Further, Colombo (1992) found out an interaction between the two distributional information, namely stress dominance and stress neighbourhood, again in her seminal work, specifically in Experiment 4 and Experiment 5. In Experiment 4 the interaction produced four kinds of low-frequency words, used as stimuli: regularly stressed words with consistent stress neighbourhood, regularly stressed words with inconsistent stress neighbourhood, irregularly stressed words with consistent stress neighbourhood and irregularly stressed words with inconsistent stress neighbourhood. The performances with regularly stressed words as stimuli were apparently not affected by the distribution of stress friends or enemies within the word stress neighbourhood; indeed, regardless of the quantity of stress friends and stress enemies within the stress neighbourhood, similarly fast reading times have been found for all regularly stressed words. According to Colombo (1992), stress neighbourhood had no effect on the performance speed with regularly stressed low-frequency words, because, since stress dominance is the main source of lexical stress assignment, the decision to assign the regular stress by default has been taken before the reader could rely on other sources of information. The composition of the word stress neighbourhood, instead, was shown to affect the reading performance in the cases of irregularly stressed word. On one hand, when irregularly stressed words with many stress friends, and, therefore, a consistent stress neighbourhood, were presented as stimuli, the performance showed approximately the same reading times and error rates as those resulting from performances with regularly stressed words. On the other hand, when irregularly stressed words with inconsistent stress neighbourhood and many stress enemies were presented as stimuli, the performance turned out to be negatively affected in speed and accuracy. According to

Colombo (1992), a highly consistent stress neighbourhood, composed mostly of stress friends, compensates for the disadvantage produced by the words irregular stress pattern and, therefore, produces naming latencies similar to the latencies of regularly stressed words. On the contrary, the presence of a large number of stress enemies and an inconsistent stress neighbourhood have the effect of slowing down the performances with irregularly stressed words. Indeed, these items do not benefit from any advantage and require more time for naming and, therefore, the responses showed longer reading times and more errors. For instance, the word *PENtola* ‘pot’ is irregularly stressed. However, the word ending *-ola* belongs to a consistent stress neighbourhood mainly associated with the irregular stress pattern in Italian, namely the antepenultimate syllable stress. Moreover, the word *PENtola* ‘pot’ has a large number of stress friends and a small number of stress enemies. Thus, when using the word *PENtola* ‘pot’ in a reading task as stimulus, despite its irregular stress pattern, the information coming from its stress neighbourhood allows regular reaction times and accuracy in the response. Further, in Experiment 5, Colombo (1992) revealed stress dominance and stress neighbourhood effects, and their interaction, in a naming task using nonwords as well.

Burani & Arduino (2004) challenged Colombo’s (1992) assumption that stress dominance is the first and main reliable nonlexical source of information for the readers and conducted two experiments on adult readers using a word naming task. The set of stimuli included low-frequency words with three and four syllables. The authors failed to report a significant effect of stress dominance and found, instead, that stress neighbourhood consistency greatly affected the performance. Indeed, the results showed that words with many stress friends were named faster and more accurately compared to words with many stress enemies, independently from the fact that the word had dominant or non-dominant stress pattern. Therefore, the authors concluded that stress neighbourhood is the main source of information for stress placement in low-frequency words and has a greater effect compared to stress dominance information. Specifically, it has been demonstrated that the stress neighbourhood consistency, namely the number of words sharing the same orthographic word ending and stress pattern with the target affects lexical stress assignment. However, not all the orthographic word endings can be informative in this respect. For instance, the word ending *-ino* has a large-sized stress

neighbourhood (1108 words ending with *-ino* in the Phonitalia database by Goslin, Galluzzi & Romani, 2013) and *-uge* has a small-sized stress neighbourhood (2 words ending with *-uge* in the Phonitalia database by Goslin, Galluzzi & Romani, 2013). Moreover, some word endings have a balanced proportion of stress friends and enemies, such as the word ending *-ile*. These kinds of endings do not provide any reliable information for readers to determine stress position. Thus, an important issue that can be discussed is how stress is assigned when neighbourhood information cannot cue lexical stress.³

Recently, Sulpizio, Job, & Burani (2012) conducted two experiments with low-frequency three-syllabic words adopting a prime paradigm to investigate again both the individual roles of stress patterns distribution knowledge and stress neighbourhood information and their interaction in the readers' performances. Confirming Burani and Arduino's (2004) results and conclusions, they failed to report a great effect of stress dominance in lexical assignment and, instead, proved the main role of the information coming from stress neighbourhood consistency and composition.⁴

Colombo and Zevin (2009) extended the results obtained with word stimuli to nonword stimuli; indeed, they conducted some experiments employing a priming paradigm with three-syllabic nonwords as stimuli. The authors found that stress dominance effect was modulated by the stress neighbourhood consistency. Indeed, when the nonword ended with an orthographic ending belonging to a consistent stress neighbourhood, stress neighbourhood effect was greater than stress dominance effect. For example, a nonword like *bistone* belongs to the dominant stress pattern neighbourhood, in fact the ending *-one* is strongly associated to the penultimate syllable stress. A nonword like *parico*, instead, belongs to the non-dominant stress pattern neighbourhood, as the ending *-ico* is strongly associated with the antepenultimate syllable stress. Despite the stress dominance knowledge, most of the readers assigned the dominant stress pattern to the first nonword (*biSTOne*) and the non-dominant stress pattern to the second (*PARico*). The authors suggested that subjects were mainly driven by the information coming from stress neighbourhood rather than the one coming from

³ For more detailed information, see Burani, C. & Arduino, L. S. (2004). Stress regularity or consistency? Reading aloud Italian polysyllables with different stress patterns. *Brain and Language*, 90, 318-325.

⁴ For more detailed information, see Sulpizio, S., Job, R., & Burani, C. (2012b). Priming lexical stress in reading Italian aloud. *Language and Cognitive Processes*, 27, Pp 808-820.

stress patterns overall distribution. Hence, they concluded that stress neighbourhood consistency and composition are more informative and reliable for the readers compared to stress dominance information in lexical stress assignment.⁵

Sulpizio, Arduino, Paizi and Burani (2013) conducted two naming experiments by using nonwords as stimuli. Nonwords were constructed to be assigned the penultimate or antepenultimate syllable stress, depending on their orthographic endings. The authors found that the information coming from stress neighbourhood consistency and composition had a greater effect on the readers' performances compared to stress dominance information. Actually, Sulpizio et al. (2013) found no evidence of a stress dominance effect at all. However, it has been noted that this is probably due to some characteristics of the nonwords chosen as stimuli (Colombo, Deguchi and Boureux, 2013). Indeed, it has been revealed that the nonwords associated with the non-dominant stress pattern had more consistent, on the average, and more numerous stress neighbourhood than nonwords associated with the dominant stress pattern. Thus, this selection might have influenced the performance and the results.⁶

Despite these results, which show a main effect of stress neighbourhood information in reading performances, stress dominance knowledge has been shown to have a role in lexical stress assignment. Indeed, researchers, by means of empirical studies on both adults and children, established that stress dominance information is not used by the readers as the default rule while assigning lexical stress to polysyllabic low-frequency words and nonwords, but rather as a general prior belief, on which they rely when other more precise sources of information lack; this is the case of beginning readers (Colombo, Deguchi, & Boureux, 2014; Sulpizio & Colombo, 2013), dyslexic young readers (Sulpizio & Colombo, 2013; Paizi, Zoccolotti & Burani, 2011; Arciuli, Monaghan & Ševa, 2010) and adults with language disorders or Alzheimer dementia (Galante, Tralli, Zuffi, & Avanzi, 2000; Laganaro, Vacheresse; & Frauenfelder, 2002; Colombo, Fonti, & Cappa, 2004). All the subjects belonging to these categories showed a bias towards the dominant stress pattern, namely the penultimate syllable stress. This means that readers with a limited lexicon and weak orthography-to-phonology

⁵ For more detailed information, see Colombo, L., & Zevin, J. (2009). Stress priming in reading and the selective modulation of lexical and sub-lexical pathways. *PLoS ONE*, 4, e7219.

⁶ For more detailed information, see Sulpizio, S., Arduino, L. S., Paizi, D. & Burani, C. (2013). Stress assignment in reading Italian polysyllabic pseudowords. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39, 51-68.

connections tend to assign the dominant stress pattern, when the lexical information is lacking. Alternatively, normal developing young readers and adult readers mainly rely on stress neighbourhood information. In support of these assumptions, Burani, Paizi and Sulpizio (2014) conducted two reading aloud experiments on both adult and fourth-grade readers. They demonstrated that fourth graders have already developed the ability to rely on stress neighbourhood information, like adults. Hence, they concluded that, as soon as beginning readers, who do not present any reading or developmental deficit, increase and assess their reading skills, the prior bias toward the dominant stress is replaced with a more specific distributional information driving the lexical stress decision, namely stress neighbourhood. Therefore, stress neighbourhood consistency and composition becomes the main source of information for lexical stress assignment in skilled readers.⁷

To sum up, considering Italian, the researchers have assessed the role of stress neighbourhood and stress dominance in the process of lexical stress assignment in polysyllabic low-frequency words and nonwords. More precisely, stress dominance information is used at a more general level, when other more specific sources of information lacks. Stress neighbourhood, instead, is used as the main source of information for skilled readers from at least the fourth-grade level of instruction. However, other sources of information might be informative for the reader and, therefore, interesting to investigate. To date, some attempts have been made in investigating the role of the grammatical category information in lexical stress assignment and the relation between syllables and stress. However, the research might be extended toward other cues to stress as well, such as the orthographic word endings and beginnings of different sizes, the length of the stimulus, namely the number of letters which compose it, or the presence of morphological units, such as prefixes or suffixes.

1.1.2 English

⁷ For a complete review on this argument, see Sulpizio S., Burani C. & Colombo, L. (2015). The Process of Stress Assignment in Reading Aloud: Critical Issues From Studies on Italian. *Scientific Studies of Reading*, 19. Pp 1-16.

English is a free-stress language and most of the English words are polysyllabic. Indeed, despite the fact that monosyllables are 70.9% in tokens, they account for only 15.5% in types, according to the CELEX database (Baayen, Pipenbrock, & Gulikers, 1995). Thus, in order to have a complete understanding of the reading process, researchers must extend their studies, including also polysyllabic units of analysis, which constitute the largest part of the English lexicon. To date, however, the reading research focused on English is restricted to disyllabic units of analysis.⁸

The first source of lexical stress information proposed for English was lexical knowledge. The prediction is that already-known words are stored in the memory and the position of the lexical stress is already established. Nonlexical sources of lexical stress information are required. Hence, researchers have to establish which nonlexical sources of information are reliable for the reader when reading low-frequency words and nonwords. To date, several hypothesis have been put forward and tested.⁹

The first nonlexical source of information proposed was stress typicality, or regularity. In English disyllabic words two kinds of stress patterns exist: trochaic and iambic. The word has a trochaic stress pattern when the lexical stress is placed on the first syllable; instead, it has a iambic stress pattern when the lexical stress is placed on the second syllable. According to the CELEX database (Baayen, Pipenbrock, & Gulikers, 1995), approximately 75% of English disyllabic words are stressed on the first syllable and, therefore, in English the dominant stress pattern in disyllables is the trochaic one. Consequently, words that are stressed on the first syllable are considered regular, or typical, and words that have final stress are considered irregular, or atypical. The results of earlier empirical researches (Paap and Noel, 1991; Jared, 2002) showed a significant effect of stress regularity in naming tasks. In addition, an interaction between stress regularity and lexical frequency was found. In more recent investigations, however, Rastle and Coltheart (2000) failed to find a significant effect of stress regularity. Indeed, performances with regularly stressed words showed neither faster reaction times nor greater accuracy than irregularly stressed words. Hence, in order to explain these results, Rastle and Coltheart (2000) reformulated the definition of stress

⁸ For further information, see Baayen, H. R., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX lexical database [CD-ROM]*. Philadelphia, PA: University of Pennsylvania, Linguistic Data Consortium.

⁹ For a detailed review of this topic, see Ktori M., Mousikou P., & Rastle K. (2018) Cues to Stress Assignment in Reading Aloud. *Journal of Experimental Psychology: General*, 147. Pp. 36-61.

regularity, or typicality. Based on Fudge's (1984) work, where it was assumed that affixes are valid lexical stress indicators, the authors implemented a computational model which included a new algorithm within the nonlexical pathway. The algorithm could detect in a given string of letters the presence of any affixes and when one was there the algorithm could refer to a database of morphemes and a set of rules to determine the correct position of the lexical stress. Specifically, the predictions made by the authors were that prefixes typically repel stress, and therefore a prefixed string of letters tends to be stressed on its last part, whereas suffixes are mainly associated to a certain stress pattern. On the contrary, when the given string of letters did not contain any of these morphological units, the sublexical mechanism was assumed to assign the regular stress pattern for English disyllables, namely first syllable stress. Rastle and Coltheart (2000) considered regular those words whose lexical stress matched the lexical stress assigned by the algorithm and irregular the words whose lexical stress contrasted with the lexical stress assigned by the algorithm. According to Rastle and Coltheart's (2000) results from experimental investigation on humans and considering their definition of regular and irregular words, regularly stressed words were pronounced faster and with less errors than irregularly stressed words. They also found a significant interaction between stress regularity and word frequency. Indeed, the results showed that the regularity effect was larger with low-frequency words and less effective with high-frequency words. Rastle and Coltheart's (2000) theory presents, however, one fundamental problem, which casts doubts on the validity of the method they used and of the conclusions they drawn. Indeed, the use of morphemic units within the sublexical mechanism results contradictory, since these units are associated with a meaning and, thus, should not be processed by the sublexical mechanism (Chateau & Jared, 2003). Hence, the subsequent researches called into question their work (Arciuli and Cupples, 2006; 2007; Mousikou et al., 2017; Ktory et al, 2018).¹⁰

One of the aspects English stress assignment investigated is the relationship between grammatical category and stress pattern. In English there is a different distribution of stress patterns among disyllabic nouns and verbs in English. Indeed, they based their analysis on corpus of disyllabic nouns and verbs and found that most of the nouns

¹⁰ For more detailed information, see Rastle, K. & Coltheart, M. (2000). Lexical and nonlexical print-to-sound translation of disyllabic words and nonwords. *Journal of Memory and Language*, 42. Pp 342-364.

exhibit a trochaic pattern of lexical stress (90%) and most of the verbs exhibited an iambic pattern of lexical stress (70%) (Sherman, 1975; Sereno, 1986; Kelly and Bock, 1988). Howard and Smith (2002) carried out an examination of disyllabic nouns and verbs in the CELEX database (Baayen et al., 1993) and confirmed that the majority of nouns have first syllable stress and the majority of verbs have final stress. Moreover, behavioural studies provided evidence in support of the assumption that grammatical category is a reliable source of information for stress assignment. Indeed, the empirical researches on adults showed that the subjects used grammatical category information to assign lexical stress, and, vice versa, used lexical stress information to establish the grammatical category. Thus, they concluded that the two information were strongly associated and confirmed the tendency to assign trochaic stress pattern to nouns and iambic stress pattern to verbs. (Smith, Baker, and Groat, 1982; Kelly and Bock, 1988). Arciuli and Cupples (2003) further investigated the typicality effect related to the grammatical category and conducted an experiment on adult English readers using a speeded grammatical classification task. Participants were presented with isolated disyllabic words and were asked to establish whether the stimulus belonged to the nouns class or to the verbs class. It resulted that trochaic nouns and iambic verbs were easier than iambic nouns and trochaic verbs, considered atypically stressed. Evidence of a stress typicality effect was demonstrated through a minor rate of errors and faster reaction times in performances with typically stressed nouns and verbs. However, using a speeded grammatical classification task to demonstrate the stress typicality effect involved grammatical processing casts some doubts on the validity of the results and conclusions. Naming and lexical decision tasks are more related to the reading process and their results would say more about the cues to stress assignment in the reading process.

Subsequently, Arciuli and Cupples (2006) called into questions the assumption that there is a straightforward correlation between grammatical category and stress pattern is straightforward. The authors suggested, instead, that it might be mediated through orthographic cues, such as words endings. In the former literature, word endings have been proposed as valid stress indicators (Smith, Baker and Groat, 1982; Kelly, Morris and Verrekia, 1998; Zevin and Joanisse, 2000). In particular, researchers suggested that the orthography of the word's coda is associated with a stress pattern. For instance, in

the word *comet*, the coda is formed by the last two letters *-et* and is associated with first syllable stress; whereas, in the word *roulette*, the coda is formed by the final sequence *-ette* and is associated with second syllable stress. However, the definition of word coda was not completely clear and the stimulus sets that have been used in their experimental studies were too small and, thus, too little informative. As a consequence, Arciuli and Cupples (2006) conducted a series of experiments with the aim of assessing the role of word endings in lexical stress assignment to disyllabic English words. Their Experiment 1 and Experiment 2, by means of naming and lexical decision tasks, showed that performance with typically stressed words, namely trochaic nouns and iambic verbs, presented much fewer errors and faster reaction times than performance with atypically stressed words, namely iambic nouns and trochaic verbs. Further, in their Experiment 3, the authors conducted a large-scale analysis of the English disyllabic words corpus, to identify first which word endings are typically associated to the trochaic stress pattern and which are associated to the iambic stress pattern, and second which word endings mainly occur in nouns and which mainly occur in verbs. Finally, in Experiment 4, they sought to determine whether readers were sensitive to non-morphological orthographic information contained in word endings; subjects were presented to a set of nonwords and asked to determine the grammatical category and the stress pattern of these stimuli. Thus, through these four experiments, they found strong evidence that word endings of English disyllabic nouns and verbs are valid orthographic cues to both grammatical category and lexical stress.¹¹

Following another similar and complementary direction, Kelly (2004) investigated the relationship between lexical stress and complexity of the word onsets. The word onset is an orthographic unit, which includes the consonant cluster preceding the first vowel of a word. For example, in the word *storm* the word onset is *st-*, in the word *time* is *t-* and in the word *angel* is absent. The author found a role of the word onset in lexical stress assignment. In a subsequent research, Arciuli and Cupples (2007) extended Kelly's (2004) investigation to orthographic units of a larger size, such as word beginnings. Word beginnings were defined as the sequence of graphemes which includes the first vowel and all the letters that precede it within a word. Thus, in the

¹¹ Arciuli, J., & Cupples, L. (2006). The processing of lexical stress during visual word recognition: Typicality effects and orthographic correlates. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, 59. Pp 920-948.

former example, the word beginnings of *storm*, *time* and *angel* are *sto-*, *ti-* and *a-*, respectively. These units were considered valid orthographic cues to lexical stress. Arciuli and Cupples (2007) conducted an analysis of the corpus of English disyllabic words and revealed that some word beginnings are mainly associated to a trochaic stress pattern and some others are more often associated to iambic stress patterns. Thus, the authors concluded that word beginnings are valid stress position indicators and contribute to some extent to lexical stress assignment.¹²

Taken together, the results provided by Arciuli and Cupples (2006) and Arciuli and Cupples (2007) suggested that both word endings and word beginnings contribute to the lexical stress assignment process. In order to assess the relative contribution of the two orthographic cues in the reading process and their reliability for beginning readers, Arciuli, Monaghan and Ševa (2010) conducted both a corpus analysis and a behavioural study. The results of the two studies showed that children were sensitive to the information associated to word endings and word beginnings. Moreover, the authors suggested that, while at the early stages of children's reading skills development the two orthographic cues have the same value, with increasing age the effect of the word endings becomes greater. Finally, Arciuli, Monaghan and Ševa (2010) compared these results with the results obtained with their computational model, in order to establish whether their model is sensitive to word endings and beginning in the same way as children. They concluded that the statistical learning mechanism used to implement their model is in line with the children's reading development.¹³

To sum up, considering English, the cues mainly investigated in the literature by researchers addressing lexical stress assignment at present are lexical knowledge, stress typicality, grammatical category, affixes and some orthographic units, such as word endings and word beginnings. However, also phonological cues to stress have been proposed in the literature. Indeed, researchers suggested that the vowel length and the syllable's phonological weight might play a role in lexical stress decision (Baker & Smith, 1976; Chomsky & Halle, 1968; Hayes, 1982; Guion, Clark, Harada and

¹² Arciuli, J., & Cupples, L. (2007). Would you rather 'embert a cudsert' or 'cudsert an embert'? How spelling patterns at the beginning of English disyllables can cue grammatical category. In A. Schalley & D.Khлentzos (Eds.), *Mental states: Language and cognitive structures* (Vol. 2, pp. 213–237). Amsterdam, the Netherlands: John Benjamins

¹³ Arciuli, J., Monaghan, P., & Ševa, N. (2010). Learning to assign lexical stress during reading aloud: Corpus, behavioral, and computational investigations. *Journal of Memory and Language*, 63. Pp 180-196.

Wayland, 2003; Kelly, 2004; Mousikou, Sadat, Lucas, & Rastle, 2017). Regarding the first cue, researchers assumed that stress fell on the syllable with the long vowel and, therefore, that readers were sensitive to the vowel length. Regarding the second cue, the phonological weight of the syllable was considered and the fact that syllables with more phonemes attract lexical stress. In conclusion, researchers engaged in the field of studies regarding lexical stress assignment in English should also include units with more than two syllables in their analysis, in order to assess a complete and more general understanding of the reading process. Moreover, they might consider other nonlexical sources of lexical stress information, such as the number of the stimulus syllables and letters, the orthographic syllable structure or the orthographic and phonological stimulus similarity to other real words.

1.1.3 Russian

Russian is a free stress language and most of the Russian lexicon is composed by polysyllables. While Russian is transparent at the segmental level, it is opaque at the suprasegmental level. Indeed, the position of lexical stress is neither predictable by any orthographic stress markers, such as diacritics, nor by determined rule. Therefore, researchers have to assess how the specific mechanism of lexical stress assignment works while processing polysyllabic words and nonwords. To date, the reading research in Russian has focused only on disyllabic units. However, a great part of the Russian lexicon includes words with more than two syllables. Therefore, researchers achieved only a limited understanding both of the more specific lexical stress assignment mechanism and of the more general reading process. Russian disyllables can exhibit two kinds of stress patterns: the trochaic stress pattern and the iambic stress pattern. Lexical stress in Russian disyllables is assigned only by means of a lexical access mechanism, according to most linguists, and any other nonlexical source of information was not considered (Melvold, 1989; Zaliznjak, 1985; Halle, 1997; Gouskova, 2010; Lukyanchenko, Idsardi, & Jiang, 2011; Moleczanow, Domahs, Knaus, & Wiese, 2013; Zsiga, 2013). Jouravlev and Lupker (2014; 2015) challenged this assumption and, by means of six studies, sought to demonstrate that readers rely on both lexical and nonlexical sources of information in assigning lexical stress to Russian disyllabic words. Further, they tested the validity of the predictions made by the Bayesian model

of lexical stress assignment against the data resulting from empirical investigation on adult Russians readers, using both words and nonwords.¹⁴

In their Study 1, the authors conducted two types of analysis with the aim of examining the distribution of the trochaic and the iambic stress patterns in a corpus of Russian disyllabic words. They found no evidence for an overall dominant stress pattern in Russian. Indeed, considering the entire corpus of Russian disyllables, they found as a result of the types-based analysis that 55% of them exhibited trochaic stress pattern and 45% of them iambic stress pattern. Similarly, the token-based analysis revealed 57% of items with the trochaic stress pattern and 43% with iambic stress pattern. However, they also examined the specific stress patterns distributions within the different grammatical categories considered separately. In this manner, they discovered in adjectives a dominance of the trochaic stress pattern, in verbs, on the contrary, a small dominance of the iambic stress pattern and in nouns, instead, no dominance of any stress pattern. Therefore, Jouravlev and Lupker conclude that, despite the balance of the two stress patterns overall, when the individual grammatical category of nouns, verbs and adjectives is separately examined, a different stress patterns distribution can be observed.

On the basis of these results, Jouravlev and Lupker (2014; 2015) conducted their Experiment 2. It consisted in a factorial investigation with the aim to establish the role of stress regularity, word endings and grammatical categories in a word naming tasks on adult Russian readers. They found no evidence for an overall stress regularity effect in the performances, both considering latencies and error rates, in line with the prior assumption that in Russian disyllables the overall distributions of the two stress patterns are balanced. However, the results showed speed and accuracy advantages in naming adjectives compared to nouns and verbs. Moreover, adjectives with the regular trochaic stress pattern were named faster and more accurately than adjectives with the irregular iambic stress pattern. Thus, stress regularity within each grammatical category plays a role in naming performance. Further, considering the role of word endings, they found that the performance was faster and more accurate when the word's stress pattern coincided with the stress pattern mainly associated to the orthographic ending of the

¹⁴ For further information, see Jouravlev, O. & Lupker, S. J. (2015b). Predicting stress patterns in an unpredictable stress language: The use of nonlexical sources of evidence for stress assignment in Russian. *Journal of Cognitive Psychology*, 27. Pp. 944-966.

word. Instead, when the word had an orthographic ending mainly associated with a stress pattern, different from the target word's stress pattern, the performance was slower and less accurate. Therefore, they could demonstrate the role of consistency of the relationship between the orthography of the word ending and the stress pattern in lexical stress assignment. In addition, they found similar results when analysing nouns and verbs, and, in contrast, different results in the analysis of adjectives. Indeed, in processing of the latter, they detected an interaction between the information given by the orthographic word endings and those from stress dominance related to the specific grammatical category. It was shown that performance with regularly stressed adjectives was not affected by the presence of an incongruent stress pattern associated to the word ending. On the contrary, performances with irregularly stressed adjectives showed an effect of this nonlexical source of information in latencies. Hence, with Study 2 the authors demonstrated that the process of lexical stress assignment in naming tasks is not based exclusively on lexical information sources, but also on nonlexical sources of information, such as, at least, stress regularity, word endings and grammatical category.

In Study 3, the authors carried out a binary logistic regressions of a set of nonlexical predictors on stress patterns in a corpus of 13,943 Russian disyllabic words. In this manner, they sought to establish the relationships between a set of nonlexical variables and stress patterns in Russian. The nonlexical predictors used were the grammatical category, the word length in letters, the word onset complexity, the word coda complexity, six orthographic components, such as the first syllable, the beginning of the first syllable, the ending of the first syllable, the second syllable, the beginning of the second syllable, and the ending of the second syllable, and the logarithmic frequency. The beginning of the first syllable represent the word beginning and the ending of the second syllable the word ending. The results of this analysis showed that, among the nonlexical cues proposed and examined, at least five are probabilistically associated with stress patterns in Russian: onset complexity, ending complexity, the orthographic structure of both syllables and the ending of the second syllable.

To further investigate the role of these five variables, Jouravlev and Lupker (2014), in their Study 4, conducted an experiment in which readers were asked to name 500 disyllabic words and the eleven nonlexical cues to stress were used as predictor variables. The five variables detected in Study 3 have been included among the eleven

predictors. The results of the analysis on the stress pattern criterion variable suggested that only three of the eleven predictor variables were used by the readers in lexical stress assignment: the two syllables orthographic structures and the ending of the second syllable. Finally, with the data and results from the latter studies, two megastudies were carried out to test whether a Bayesian model of stress assignment was able to predict stress patterns in Russian disyllabic words and nonwords (see paragraph 3.1).¹⁵

To sum up, considering Russian, the sources of lexical stress information proposed have been word knowledge as first and, later on, nonlexical cues to stress, which are, in particular, the two syllables orthographic structures and the ending of the second syllable. However, the reading research in Russian reading has focused exclusively on disyllabic units. Therefore, the future research should extend the field of studies to other units with more than two syllables. In this manner, researchers can make headway in assessing the general process of reading.

¹⁵ For more detailed information, see Jouravlev, O., & Lupker, S. J. (2014). Stress consistency and stress regularity effects in Russian. *Language, Cognition and Neuroscience*, 29. Pp. 605-619.

2 Computational models of reading aloud single words: an overview

All the theories and theoretical studies regarding the reading process led to the implementation of computational models, which can simulate the human behaviour in reading aloud single words and nonwords. With the computational models contribution, researchers can not only increase their knowledge about the reading process functioning, but also observe causes and effects of a reading disorder in concrete. In this chapter, the most significant studies, theories and models will be described that have attempted to represent and simulate the human cognitive behaviour when involved in the task of reading aloud isolated words or nonwords in a computational manner.

The first part of the chapter presents the historical background that led to the emergence of a computational approach to study the process of reading aloud isolated strings of letters. Attention is focused on the two most influential theories, which contributed to create a well-functioning structure of the proposed models: connectionism and dual-route theories. The aim of this part is to clarify the framework and foundations along which the computational models have been developing.

The second part of this chapter offers a detailed description and analysis of the most significant and influential computational models. The models under discussion are divided into two categories according to their object of study: the older monosyllabic models of reading aloud, mostly based on data from the English language, and the more recent polysyllabic models of reading aloud. For the first class of models, we chose to consider the Triangle Model provided by Seidenberg and McClelland (1989) and its latest developments (e.g. Plaut et al., 1996; Harm & Seidenberg, 1999), the Dual-Route Cascaded (DRC) model of Coltheart and colleagues (Coltheart et al., 1993, 2001; Coltheart & Rastle, 1994; Rastle & Coltheart, 2000; Ziegler, Perry, & Coltheart, 2000, 2003), and the Connectionist Dual Process (CDP) model of Zorzi et al. (1998b) and its successor CDP+ of Perry et al. (2007). For the second class of models, we decided to deal with the model of stress assignment of Ševa et al. (2009), the model of reading of Pagliuca and Monaghan (2010), and the most recent version of CDP and CDP+ models,

the Connectionist Dual Process ++ (CDP++) model of Perry, Ziegler and Zorzi (2010; 2014, based on Italian data).¹⁶

The chapter ends with the discussion on a brand new approach related to the study and interpretation of the process of reading aloud, that is represented by the Bayesian models of reading aloud.

2.1 The historical background of a computational approach

The first attempts to give an explanation of how the cognitive system works in the task of reading aloud single words began in the 19th century and were purely descriptive and verbal. Indeed, researches presented their proposals in a qualitative way, generally using box-and-arrow diagrams to represent the process under discussion. However, these models presented fundamental shortcomings and limitations, because a purely descriptive approach is far from being well-suited to represent the practical function of the process, as we shall see.¹⁷

Therefore, at least since the second half of the 19th century, scientists have gradually been changing their qualitative approach into a quantitative approach, by introducing the use of maths and algorithms in this area of studies; the result was the pursuit of a more modern tool, more explicit and detailed, which could replace the outdated verbal models: the computational models, already known in the area of cognitive sciences. Computational models are, in general, computer programs created to simulate a cognitive human behaviour in an accurate and quantitative manner. From the 1980s, cognitivists introduced this type of models in their studies on the cognitive human behaviour of reading aloud isolated words, in order to understand the complex mechanism which underlies it. The starting point to design computational models came from the former verbal theories. The computational approach brought the big advantage of producing quantitative results, which could be subsequently compared with the human data in the same task. In this way, researchers could understand whether the implemented model worked correctly or should have been improved. Another

¹⁶ The models proposed for both categories have been several, but we decided to analyse only the most famous and influent of them in our discussion. For a more detailed review, see Zorzi, M. (2005). Computational models of reading. In G. Houghton (Ed.), *Connectionist models in cognitive psychology*. London: Psychology Press. Pp 403–444.

¹⁷ For a more detailed review, see Jacobs, A. M. & Grainger, J. (1994). Models of visual word recognition: Sampling the state of the art. *Journal of Experimental Psychology: Human Perception and Performance*, 20 (6). Pp 1311–1334.

advantage of the computational models was the possibility to manipulate their inner structure so that it could not only be observed and improved, but also modified to simulate cognitive human disturbances better, such as dyslexia. The first computational models which simulated the process of reading aloud single words emerged from two main verbal theories: connectionism and dual-route theories.¹⁸

2.2 Connectionism and dual-route theories in comparison

The two most influential theories which contributed to create the current structure of the computational models of reading aloud are connectionism and dual-route theories.

Developed in a period when the attention of a large number of scientists was focused on neurology and neuropsychology, connectionism was seeking to create an analogy between the biology of the brain and the connectionist models. Indeed, the assumption was that the architecture of the models reflected the structure of the neural network, in order to simulate cognitive behaviour. Connectionist models were generally implemented at least with 3 layers: input units, output units and hidden units. The role of the hidden units was to compute complex rules that could not be performed by simple feed forward, two-layers network. The units which form the layers are simple processing neuron-like elements, linked to each other by weighted connections. Once the stimulus is presented to the model, the input units become active and spread the activation to the entire structure. With repeated exposure to the network, the weighted connections can be adjusted to improve the performance of the model. When a connectionist model is completely implemented, it first goes through a phase of training; during this phase it is presented a set of stimuli from which it learns, for example, the correspondences between the strings of letters and their correct pronunciation. Then, the collected information is distributed among the entire network and can be processed anywhere in the structure. In order to make the training phase more effective, the model uses learning algorithms, like, for instance, the most common backpropagation algorithm (Rumelhart, Hinton, and Williams, 1986). Hence, after the training phase, the weighted connections are adjusted and the model becomes more accurate and efficient over time and experience. One issue that was investigated using

¹⁸ For more detailed information, see Seidenberg, M. S. (2012). Computational models of reading: Connectionist and dual-route approaches. In Spivey M., McRae K., & Joanisse M. (Eds.), *Cambridge handbook of psycholinguistics*. Cambridge University Press. Pp 186–203.

this type of networks is whether a single mechanism serves to represent both regular and exception words. The emblematic model proposed in the connectionist framework is today known as Triangle model and will be described in detail in the paragraph 1.3.1.¹⁹

In the 20th century, before the connectionist vision became popular, another opposite vision was prevalent among cognitivists and neuropsychologists, especially among those who conceived the language-processing system as a multicomponent modular system with local representations. They believed that the mechanisms underlying the cognitive processes involving language worked in a serial manner with local represented units and was governed by rules. This movement had already started in the 1960s, when Morton (1964; 1968) proposed his Logogen model to explain the cognitive processes of both spoken and written speech recognition and spoken word production, using logogens as specialized recognition units; this model, like its contemporaries, was described in a qualitative and verbal way, with box-and-arrow notations. Later on, starting from the 1980s, several other authors revived Morton's approach and proposed their still exclusively verbal generalizations of his model, maintaining the concept of localized units (e.g., Ellis & Young, 1988; Harris & Coltheart, 1986; Patterson & Shewell, 1987). The first attempt to implement a computational model relying on Morton's approach was made by McClelland and Rumelhart (1981) with their Interactive Activation and Competition (IAC) model for visual word recognition, further developed also by Jacobs and Grainger (1992) and Grainger and Jacobs (1996). Subsequently, Coltheart et al. (1993) started to implement the Dual-Route Cascaded (DRC) model based on the IAC model for visual word recognition, but added the division between lexical and nonlexical route for reading aloud. The Dual-Route Cascaded (DRC) model described by Rastle and Coltheart (2000) and Coltheart, Rastle, Perry, Langdon and Ziegler (2001) is the complete version of the dual-route theory and it will be described in detail in paragraph 1.3.2 and 1.4.1.

The dual-route model architecture consists of two pathways: the lexical route and the sublexical route. The lexical route is specific for the familiar and high-frequent words, which would be represented in a mental lexicon. The sublexical route is instead assumed to process unknown and less-frequent words, broken down into smaller units;

¹⁹ For more detailed information about connectionist theory and models, see Seidenberg, M. S. (2005). Connectionist models of word reading. *Current Directions in Psychological Science*, 14. Pp 238-242.

this pathway follows specific rules to achieve the right correspondence between orthographic and phonetic units and, therefore, the correct pronunciation of the word. Since it works with rules, this route is not suitable to process irregular or exception words. Many experimental studies have shown that irregular words show longer reaction times to be read aloud than regular words and this delay is due to the fact that the two routes are independent and produce two different outputs, so that the resolution of this conflict takes more time. This effect, however, interacts with the frequency of the word, so that the effect of regularity in the correspondence only occurs for low-frequency words. Dual-route models seek to explain both the normal reading behaviour and the acquired and developmental disorders of reading (Jared, 1997).²⁰

The dual-route model and the connectionist model show some fundamental differences, which can be summarized as follows:

- The model's architecture: while dual-route theories assume that two independent mechanisms are necessary to represent regular and exception words, earlier versions of connectionist models compute them within a single mechanism. However, the most recent versions of the connectionist models include the semantic component as well;
- The nature of processing: while the connectionist models assume that the mechanism works in parallel, which means that all the letters and information are processed simultaneously, the sublexical route of the dual-route models works serially, which means that it proceeds from left to right, transcoding one letter after another to the corresponding sound;
- The nature of representation: while the dual-route theory assumes that the information is locally represented and, therefore, in the models of reading aloud single word, each word corresponds to a single unit in the lexicon, the connectionist vision suggests the contrasting idea of a distributed representation, which means that the information concerning a given word is equally distributed among all the structure units, which all together contribute to achieve the final result;

²⁰ For more detailed information, see Coltheart M. (2005). Modeling Reading: The Dual-Route Approach. In Snowling M. J. & Hulme C. (Eds.), *The Science of Reading: A Handbook*. Oxford: Blackwell. Pp 6-23.

- Learning: connectionist models learn the orthography-phonology correspondence through a phase of training during which an algorithm adjusts the strengths of the connections between units, so that it becomes more accurate in the responses over time; this process should mirror the process through which the children gradually acquire the reading competence by exposure. In contrast, in interactive activation models and following developments the nodes corresponding to each word have an associated activation value that is determined by researchers following specific assumptions.²¹

2.3 Monosyllabic models of reading aloud single words

The first implemented models of reading aloud single words have been developed exclusively for English monosyllables. Researchers started considering only these simple units for two logical and practical reasons. First, they found it easier to understand the process starting small, and this means starting from one syllable at a time; the combination of more syllables was considered a more complex issue, involving stress location as well, and would have been investigated later on, when the knowledge about single units would have been more accurate. Secondly, at the moment the models started to develop, the available experimental data and relative literature included nearly exclusively information about monosyllabic units, and, therefore, researchers had a wider knowledge about them than about more complex units, as well as a larger set of stimuli to test the models.

Among the several models proposed, the most significant monosyllabic models of reading aloud are the Triangle Model provided by Seidenberg and McClelland (1989) and its latest developments (e.g. Plaut et al., 1996; Harm & Seidenberg, 1999), the Dual-Route Cascaded (DRC) model of Coltheart and colleagues (Coltheart et al., 1993, 2001; Coltheart & Rastle, 1994; Rastle & Coltheart, 1999; Ziegler, Perry, & Coltheart, 2000, 2003), and the Connectionist Dual Process (CDP) model of Zorzi et al. (1998b)

²¹ For more detailed information, see Coltheart, M. (2006). Dual route and connectionist models of reading: An overview. *London Review of Education*, 4 (1). Pp 5-17.

and its successor CDP+ of Perry et al. (2007). This models will be described in detail in the following paragraphs.²²

2.3.1 The Triangle Model

The Triangle model originated from the three-layer connectionist network implemented by Seidenberg and McClelland (1989), in which input and output units represented respectively the orthographic and phonological form of the given string of letters; therefore, in this process, the phonology of the printed word or nonword was derived from its orthographic representation.²³

Later on, an improved version has been developed by Plaut et al. (1996), where the highly distributed Wickelfeature representation was replaced by a more localist coding of orthographic and phonological units and the semantic component was included in the model.²⁴

Finally, the most recent version of the model was provided by Harm and Seidenberg (2004). The latest version includes both the orthographic and phonological components and a semantic component, with the task to compute the meaning of the printed string of letters. The semantic component was included in the model because understanding is a fundamental part of the reading process. The model provides two pathways from spelling to sound: the direct orthography-to-phonology pathway and the pathway which maps orthography to phonology through semantics (see Figure 1).

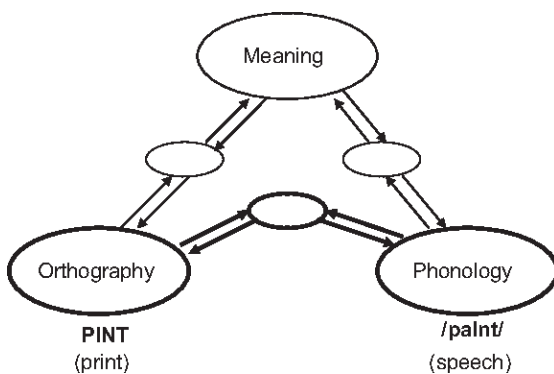


Figure 2. The standard connectionist Triangle model, from Perry, C., Ziegler, J. C. & Zorzi, M. (2007). The part provided first by Seidenberg and McClelland (1989) is shown in bold.

the direct orthography-to-phonology pathway and the pathway which maps orthography to phonology through semantics (see Figure 1).

In the model, a set of printed stimuli is presented to the network as a training set and the model learns to perform their correct pronunciation; the model can do this task properly first because it is exposed

²² For a more detailed review, see Zorzi, M. (2005). Computational models of reading. In G. Houghton (Ed.), *Connectionist models in cognitive psychology*. London: Psychology Press. Pp 403–444.

²³ For more detailed information, see Seidenberg, M. S. & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, 96. Pp 523-568.

²⁴ For more detailed information, see Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. E. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review*, 103. Pp 56-115.

to a high number of examples of orthography-phonology transcoding during the training phase, second, it is provided with a learning algorithm which finds the appropriate set of weights to adjust the connections between units. The Triangle model uses the error backpropagation algorithm (e.g. Rumelhart et al., 1986), a generalization of the delta rule algorithm (Widrow and Hoff, 1960) that allows training of multilayer networks and can adjust the connections between units and improve the model's performance.²⁵

The last version of the model was shown to perform good in words and nonwords reading. Indeed, after the training phase, during which it has been presented with 1.5 million words, the model correctly produced the semantic representations for 97,3% of the items and the phonological representation for 99,2% of the items. Moreover, the model accounted for many aspects and effects of the process of reading aloud single words and nonwords, both of normal skilled readers and of people with reading disorders (e.g. dyslexia). Indeed, it was able to simulate the interaction between word frequency and spelling-sound regularity, the consistency effect and homophone and pseudohomophone effects. However, the model also presents some limitations. First, the error back-propagation algorithm is currently considered implausible from both a psychological and neurobiological point of view. Moreover, the model does not account for important serial effects in reading aloud, like the length effect (demonstrated by Weekes, 1997) and the position-of-irregularity effect (demonstrated by Coltheart & Rastle, 1994; Rastle & Coltheart, 1999; Roberts, Rastle, Coltheart, & Besner, 2003). Lastly, it was shown to be lacking in predicting item-level variance.²⁶

2.3.2 The Dual-Route Cascaded model

The Dual-Route Cascaded (DRC) model is the computational realization of the dual-route theory of reading. It was implemented by Coltheart and colleagues (Coltheart et al., 1993, 2001; Coltheart & Rastle, 1994; Rastle & Coltheart, 1999; Ziegler, Perry, & Coltheart, 2000, 2003), as a counter-proposal to the already known connectionist approach. The first version of the model was created to process only simple

²⁵ For further information, see Harm, W. M. & Seidenberg, M. S. (2004). Computing the meanings of words in reading: Cooperative division of labor between visual and phonological processes. *Psychological Review*, 111. Pp 662–720.

²⁶ For more detailed information, see Perry, C., Ziegler, J. C. & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: the CDP+ model of reading aloud. *Psychological Review*, 114. Pp 273-315.

monosyllabic units, but gradually more components which are used for the computation of polysyllabic units have been developed. The last version of the model, including new components for polysyllabic words and nonwords, will be described in detail in paragraph 1.4.1.

The Dual-Route Cascaded (DRC, Coltheart et al., 2001) model (see Figure 2) works serially and the process starts when the printed string of letters is detected and analyzed processing first the visual feature units and then the letter units. Two different and independent processes are working in the model: the lexical route and the sublexical route. The lexical component processes the given string of letters by means of parallel spreading activation. The lexical route in turn also presents two alternative routes: one goes directly from the orthographic component to the phonological component, and the other is connected to phonology through the semantic component. The sublexical component works in a serial way, proceeding from left to right and applying a number of grapheme-to-phoneme correspondence (GPC) rules. Considering the way the two routes work, the lexical route is more suitable and faster for already known words, and is required for exception words, which, by definition, don't follow the language specific grapheme-phoneme correspondence rules (e.g. for English the pronunciation of *ea* in *head* vs *bead*). In contrast, the nonlexical route is necessary for reading nonwords, because they don't exist in the lexicon of the language taken into account and, therefore, they are not stored in the reference mental lexicon.

The Dual-Route Cascaded (DRC, Coltheart et al., 2001) model has succeeded in implementing both the reading-aloud task and the lexical decision task. Regarding word reading the model performance was almost perfect. Indeed, the model produced only 83 incorrectly read words within a set

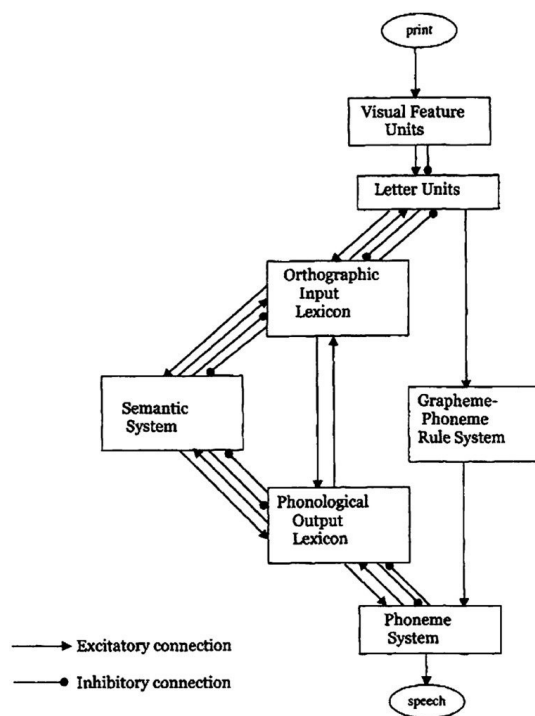


Figure 3. The Dual-Route Cascaded (DRC) model of visual word recognition and reading aloud. From Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. (2001).

of 7981 words in total. In nonword reading the error rate was low as well. The authors tested the model in a set of 7000 monosyllabic nonwords with from three up to seven letters chosen randomly from the ARC Nonword Database (Rastle, Harrington, Coltheart, & Thomas, 2000) and the model produced only 75 errors. Moreover, it simulated several important effects, like, for instance, the length effect, the frequency effect, the regularity effect and their interaction, and it also can explain some serial effects, like the position of irregularity effect.²⁷

Even if nowadays there is strong agreement among reading theorists that two kinds of procedures are necessary to translate printed words and nonwords from orthography to phonology, the way the model works presents some fundamental limitations. The most important ones are the absence of learning and the presence of complex context-specific or phonotactic output rules, that cannot be suitable to simulate either normal reading development or developmental reading disorders. Moreover, the model cannot account for the graded consistency effect demonstrated by Glushko (1979). In Experiment 3, he found a distinction between regular words with consistent neighbourhood and regular words with inconsistent neighbourhood. With neighbourhood the author meant the set of the words that the word resemble. When the pronunciation of the regular word, with regular spelling-to-sound correspondence, was consistent with its neighbourhood, the naming latencies were lower. However, the more exceptional words within the word's neighbourhood, the more inconsistent the word neighbourhood is and the higher the naming latencies, a delay typically reported for irregular words. Specifically, Glushko (1979) found that the regular and consistent words *haze* and *wade* were named faster than both the regular and inconsistent word *wave* and the exception word *have*. The DRC model is not able to simulate the above described effect.²⁸

²⁷ For more detailed information, see Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, 108. Pp 204-256.

²⁸ For more detailed information, see Perry, C., Ziegler, J. C. & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: the CDP+ model of reading aloud. *Psychological Review*, 114. Pp 273-315.

2.3.3 The Connectionist Dual Process models

In an atmosphere of debate between connectionism and dual-route theories, a model which represents the combination between the two approaches has been proposed by Zorzi et al. (1998b); indeed, the so called Connectionist Dual Process (CDP) model associates some features of the Triangle model with some of the DRC model (see Figure 3). The model presents in its structure the distinction between the lexical route and the sublexical route, typical of the dual-route models. However, both routes are built with a classic connectionist architecture and work following the principles of parallel-distributed processing (PDP) models. In Zorzi et al. (1998b) the sublexical route was implemented as a fully parallel simple two-layer associative (TLA) network, that maps orthography directly onto phonology, without the mediation of hidden units.

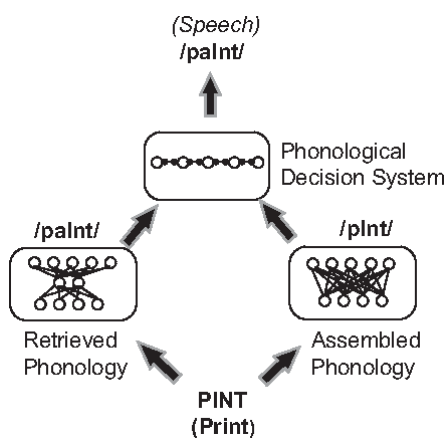


Figure 4. The Connectionist Dual Process (CDP) model. From Zorzi, M., Houghton, G. & Butterworth, B. (1998a).

This phonological assembly process extracts the statistically most reliable spelling-sound relationship in English, but does not form representations of the individual items; therefore, the TLA network produces regularized pronunciations of exception words and it is not sensitive at all to the base-word frequency of the target word. Instead, it is highly sensitive to the statistical consistency of spelling-sound relationships at multiple grain sizes, from letters to word bodies. Since the TLA network is unable to

achieve the correct pronunciation of exception words, this task must be carried out through a mediated mapping, based on lexical nodes. Zorzi et al. (1998b), therefore, implemented the frequency-sensitive lexical pathway, conceptualized as an interactive activation three-layers network (it works with the mediation of hidden units) based on lexical knowledge. The lexical route allows the possibility to use either a distributed or a localist implementation of the lexical network, but Zorzi et al (1998b) used the localist version. The output of the two routes converge on the phonological decision system, which produces the final pronunciation. The phonological decision system decides which of the two outputs to activate on the basis of competition. This step takes more time in the case of low frequency and exception words, because in most cases the two

pathways produce different output. Therefore, in the processing of these units an increase of naming latencies occurs. In the case of regular words the naming latencies are not delayed, since the two pathways produce the same output and the phonological decision system do not need more time to make its decision. The model differs from the Triangle model for the algorithm it uses: while the triangle model works with the backpropagation algorithm (e.g. Rumelhart et al., 1986), the CDP model uses the delta rule algorithm (Widrow and Hoff, 1960), the simplest learning algorithm among the many, widely applied to human learning.²⁹ When tested, Zorzi et al.'s (1998b) CDP model revealed good performance in some aspects of the process of reading aloud of single words and nonwords, like the consistency effect. However, it also presented some challenging aspects; for instance, it was not able to simulate some serial effects, like the length effect and the position-of-irregularity effect.³⁰

Perry, Ziegler and Zorzi (2007) further improved the earlier model and through a qualitative evaluation of the models described so far considered the aspects in which

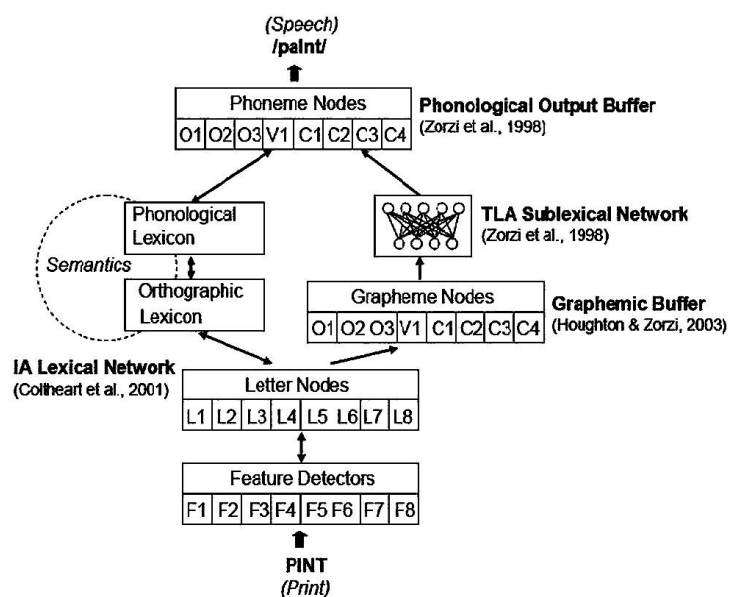


Figure 5. The Connectionist Dual Process + (CDP+) model of reading. From Perry, C., Ziegler, J. C. & Zorzi, M. (2007).

each model performed. The new model they proposed was created following the nested-modeling principle, which requires that the resulting model is related to, or included, the direct precursors; in this manner, it should overcome the limitations of the previous models. The result was the Connectionist Dual Process + (CDP+) model, a combination between the best

²⁹ For further information, see Zorzi, M., Houghton, G. & Butterworth, B. (1998b). Two routes or one in reading aloud? A connectionist dual-process model. *Journal of Experimental Psychology: Human Perception and Performance*, 24. Pp 1131– 1161.

³⁰ For more detailed information, see Perry, C., Ziegler, J. C. & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: the CDP+ model of reading aloud. *Psychological Review*, 114. Pp 273-315.

features of some of the previous models, developed into a single new model (see Figure 4). As it can be deduced from the name, the model can be considered an updated version of the CDP model, but the architecture of the new model combines some aspects both of the CDP and the DRC model. When a printed string of letters is presented to the model as an input, the process starts with processing units at the feature detectors level and then at the letter nodes level. At this point of the process, two routes are implemented. The lexical route works like the symbolic localist lexical network of the DRC model, based on the interactive activation model of McClelland and Rumelhart (1981). The sublexical route works like the TLA sublexical network of the CDP model. In order to improve learning of spelling-sound correspondence, Perry et al. (2007) used graphemes instead of single letters as orthographic input; graphemes are retrieved by a serial graphemic parsing of the string of letters from left to right. Units are encoded at the graphemic buffer level through a CCCVCCCC syllabic structure and then transcoded into phonemes. The two routes only interact in the phonological output buffer to produce the final pronunciation, after a competition between the different outputs.³¹

The CDP+ model performed better than the previous dual-route models in the task of reading aloud isolated words and nonwords overcoming the shortcomings of the former models. Indeed, when tested in a naming task with the 7383 monosyllabic words of its lexicon as stimuli, the model performed almost perfectly, with an error rate of 1,33%. Further, the model was tested in a nonword reading task with a set of 592 stimuli. The same corpus of nonwords was previously tested on 24 English skilled readers. The model produced a 37 errors, which is the 6,25% of the total responses. The model error rate was compared with the error rate from the human performance and it was found that the human error rate was similar to the model error rate (7,3%). Thus, the model successfully simulated the human reading aloud single words and nonwords. However, this model, as well as the others described so far, presents a fundamental intrinsic limitation, which is the possibility to process only monosyllabic units.

³¹ For more detailed information, see Perry, C., Ziegler, J. C. & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: The CDP model of reading aloud. *Psychological Review*, 114. Pp 273–315.

2.4 Polysyllabic models of reading aloud single words

At this point, one can claim that the models described so far, especially CDP+ model, are remarkably successful in the task of reading aloud isolated words and nonwords. However, we have to take into account that these models all have in common an important aspect which is considered an intrinsic fundamental limitation: in the task of reading aloud isolated words and nonwords, they only process monosyllabic units and do not account for more complex units of analysis, which are represented by polysyllables. The lexicons of many languages is mostly composed by polysyllabic words, while in many languages monosyllables are just a small part of the lexicon. Therefore, if we want to accurately simulate the process of reading aloud single words and nonwords, we must include the possibility to process polysyllabic items. Hence, we can conclude that the monosyllabic models of reading aloud single words are not able to account for the reading process in its entirety and complexity.

To overcome this limitation, researchers started to design new models or improve the existing models with new components or networks, in order to represent the processing of polysyllabic strings of letters. This led to additional problems to solve. Indeed, when scientists began to use polysyllabic words or nonwords as stimuli, they had to deal with more complex issues, such as lexical stress assignment, syllabification, relationship between segmental and subsegmental information and vowel reduction. A more detailed analysis of these issues will be given in chapter 2.

Among the several models proposed, the best contribution was given by the models implemented by Rastle and Coltheart (2000), Ševa et al. (2009), Pagliuca & Monaghan (2010) and Perry, Ziegler and Zorzi (2010), which will be described in detail in the next paragraphs. Moreover, other, perhaps less popular models have also been proposed, like the Multi-Trace model of Ans, Carbonel and Valdois (1998) and the Junktion model of Kello (2006), which will not be considered in the present study.

2.4.1 The model of Rastle and Coltheart (2000)

Rastle and Coltheart's (2000) model is an extended version of the Dual-Route Cascaded (DRC) model, previously described in paragraph 1.3.2, implemented in order to also simulate the reading of disyllabic units of analysis. One of the main issues that was to be solved in attempting to model disyllables was how and when within the

process the reader assigns lexical stress. Understanding the process of lexical stress assignment is particularly critical for those languages in which the position of the lexical stress is neither predictable by rules nor orthographically marked (e.g. English and Italian), and, at the same time, it is fundamental, since establishing the correct position of the lexical stress is a fundamental step in the reading aloud process.³²

Rastle and Coltheart's (2000) maintained the dual-route structure of the original model, including the two independent pathways: the lexical route and the sublexical route. Regarding the processing of disyllables, they assumed that the lexical route was not problematic for lexical stress assignment. Indeed, this pathway accounts for both already-known monosyllabic and disyllabic words, which are stored in the mental lexicon with all their intrinsic information, among which the information about lexical stress position, which can, therefore, be easily retrieved. Regarding the sublexical route,

Rastle and Coltheart (2000) proposed a rule-based algorithm (see Figure 5), which could detect the presence of affixes in the printed string of letters. In English affixes are considered a valuable source of lexical stress information.

Indeed, some suffixes bear stress and other

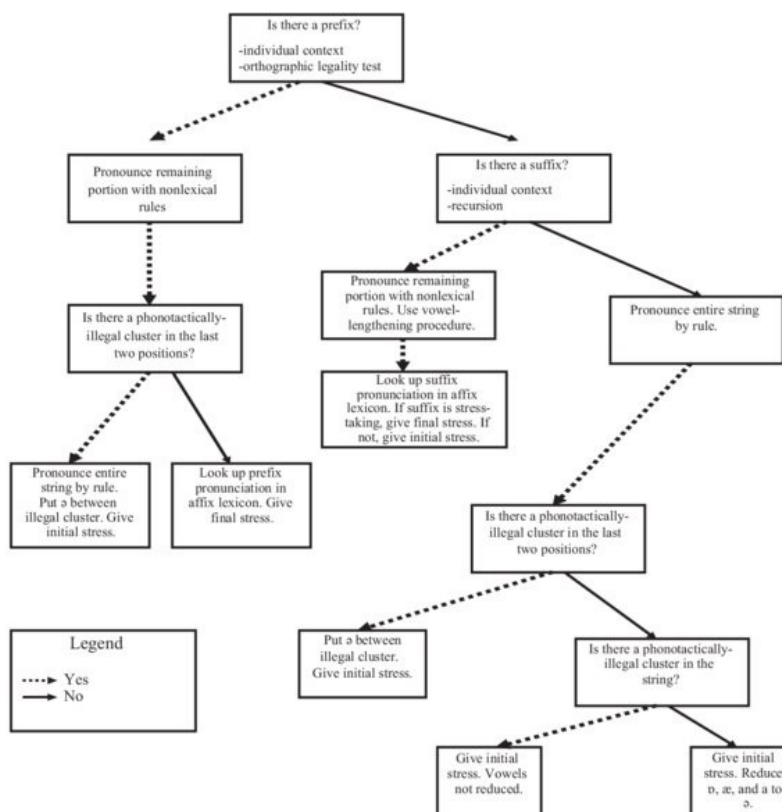


Figure 6. The rule-based-algorithm of Rastle and Coltheart (2000). From Mousikou, P., Sadat, J., Lucas, R. & Rastle, K. (2017).

³² A long and detailed treatment of this issue will be offered in chapter 2.

do not bear stress, therefore, suffixes, in general, are good stress indicators. Prefixes, instead, has the characteristic to repel stress. This assumption is important for example in the investigation of the English disyllables, because researchers could observe whether the presence of a prefix cause a bias in favour of the final stress. Thus, if the string of letters contained prefixes or suffixes, the correct stress placement was assigned by the algorithm referring to them. On the contrary, if the string of letters did not contain any prefix or suffix, Rastle and Coltheart (2000) assumed that the lexical stress was assigned based on the prevalent stress pattern of English, which has been shown to be the first syllable stress.³³

The model has shown good performance in assigning stress to disyllabic word and nonwords. Indeed, when tested on the CELEX database (Baayen, Piepenbrock & van Rijn, 1993), the model managed to assign stress correctly for 92.5% of words with first syllable stress and for 75.6% of words with second syllable stress. The model was also tested on two nonword datasets: Rastle & Coltheart (2000) and Kelly (2004). On the first dataset, it correctly assigned stress on 93.0% of the stimuli with first syllable stress and on 74.9% of the stimuli with second syllable stress. On the second dataset, it correctly assigned stress on 78.2% of the stimuli with first syllable stress and on 43.8% of the stimuli with second syllable stress.³⁴

However, the structure of the model and the way it works involve some aspects which have to be revised. One problematic issue, for instance, is the treatment of stress assignment as a process which happens at the segmental level and consequently the absence in the architecture of a suprasegmental level of processing. The independence of segmental and suprasegmental levels is a current matter of debate among researchers, but it seems plausible that the two levels are separate and that both contribute to an efficient processing of the stimuli during the reading process.³⁵ Another aspect which calls into question the effectiveness of the model is the way the algorithm works within the sublexical route; since the sublexical pathway works serially in a left-to-right

³³ For further information, see Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, 108. Pp 204-256.

³⁴ For further information, see Perry, C., Ziegler, J. C., & Zorzi, M. (2010). Beyond single syllables: Large scale modelling of reading aloud with the Connectionist Dual Process (CDP++) model. *Cognitive Psychology*, 61. Pp 106–151.

³⁵ For a more detailed review, see Sulpizio, S., Burani, C., & Colombo, S. (2015). The Process of Stress Assignment in Reading Aloud: Critical Issues From Studies on Italian. *Scientific Studies of Reading*, 19. Pp 1–16.

manner, the algorithm could have some difficulties to detect and elaborate the suffixes which are located at the end of the training word or nonword. Lastly, the model does not consider the level of syllable representation, and therefore cannot account for the relationship between syllables and stress and its relative effects.³⁶

2.4.2 The model of Ševa et al. (2009)

Ševa et al. (2009) developed a distributed-connectionist network for English, which accounted for the process of stress assignment in the task of reading aloud single words and nonwords (see Figure 6). The proposed network learns to map an orthographic input onto a stress pattern in a simple feedforward manner, but does not provide a pronunciation or reaction time. The model's architecture has three layers. The first layer consists of 364 orthographic units, which means that it can accommodate 26 letters in 14 slots. The second consists of 100 hidden units, which mediate between the first and the last layer. The third layer consists of 1 output unit, which, as a result of the elaboration, computes whether stress is on the initial or final syllable.

The model, like Rastle and Coltheart's (2000) rule-based algorithm, was tested on the CELEX database (Baayen, Piepenbrock & van Rijn, 1993) and on two nonword datasets: Rastle & Coltheart (2000) and Kelly (2004). On the first database, the model correctly assigned stress for 97.0% of words with first syllable stress and for 77.0% of words with second syllable stress. On the second dataset, the model obtained 87.7% and 49.5% correct classifications for nonwords with first syllable stress and nonwords with second syllable stress, respectively. On the third dataset, it obtained 88.6% and 42.2% correct classifications for nonwords with first syllable stress and nonwords with second syllable stress, respectively. Thus, compared to Rastle & Coltheart's (2000) algorithm, Ševa et al.'s (2009) model performed slightly better on disyllabic words and Kelly's (2004) disyllabic nonwords, but it showed inferior performance on Rastle & Coltheart's (2000) disyllabic nonwords. Regarding nonwords, both models have shown the

³⁶ For further information, see Mousikou, P., Sadat, J., Lucas, R. & Rastle, K. (2017). Moving beyond the monosyllable in models of skilled reading: Mega-study of disyllabic nonword reading. *Journal of Memory and Language*, 93, 169–192.

tendency to also assign first-syllable stress to nonwords which, according to the majority of human readers, required second-syllable stress.³⁷

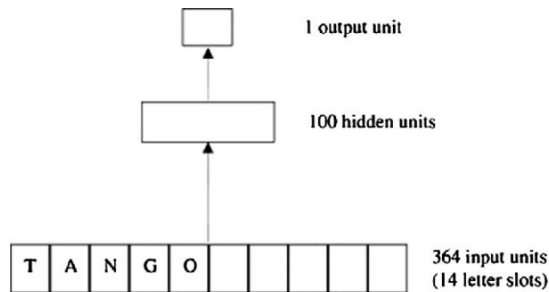


Figure 7. The Ševa et al. (2009) model of stress assignment. From Mousikou, P., Sadat, J., Lucas, R. & Rastle, K. (2017).

2.4.3 The model of Pagliuca & Monaghan (2010)

The models described so far accomplished the task of reading aloud English words and nonwords; English is peculiar because it has a quasi-regular, or deep, relationship between orthography and phonology. Pagliuca and Monaghan (2010) proposed a single-route connectionist model for Italian, a language which presents a more transparent, or shallow, relationship between orthography and phonology, than English.³⁸ The architecture of the model is a classic connectionist architecture, consisting of three interconnected layers: orthographic units, hidden units and phonological units. The orthographic and phonological information is represented within the respective layers in syllable units, with each syllable composed of onset, nucleus and coda.³⁹ Stress is considered a segmental feature both in the orthographic layer and in the phonological layer and, therefore, a suprasegmental level is absent from the model.⁴⁰

When tested, the model showed good performance in reading words; indeed, it correctly assigned lexical stress for 93.7% of the stimuli and demonstrated particular sensitivity to the morphology, even though it has no morphological processing layers, and to the stress neighbourhood. However, it showed inferior performance in reading

³⁷ For further information, see Perry, C., Ziegler, J. C., & Zorzi, M. (2010). Beyond single syllables: Large scale modelling of reading aloud with the Connectionist Dual Process (CDP++) model. *Cognitive Psychology*, 61. Pp 106–151.

³⁸ The concepts of *shallow* and *deep* in regard to the relationship between the orthography and phonology of a given language will be explained better in chapter 2.

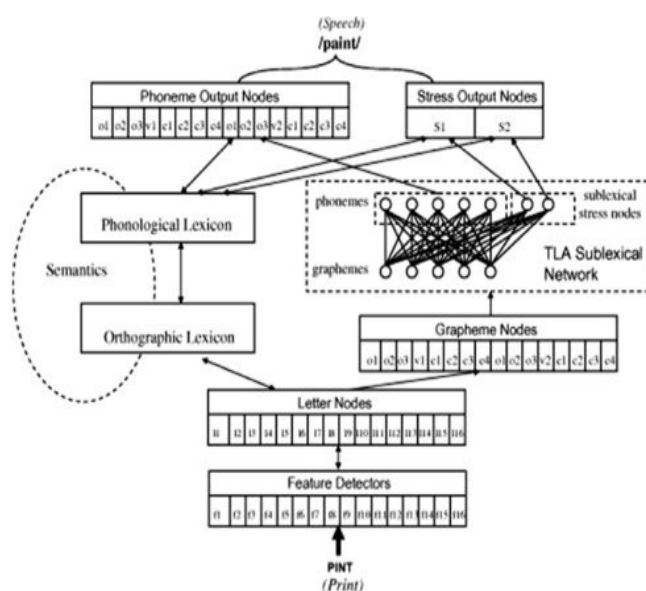
³⁹ More information on the inner structure of a syllable will be provided in chapter 2.

⁴⁰ For further information, see Pagliuca G. & Monaghan P. (2010).

and assigning lexical stress to nonwords based on three nonword datasets: Arduino et al. (2004), Burani et al. (2008) and Pagliuca et al. (2008). In particular, the model did not account for the stress neighbourhood consistency and pseudohomophone effects and the main effect of the stress dominance.⁴¹

2.4.3 The Connectionist Dual Processing ++ (CDP++) model of Perry, Ziegler and Zorzi (2010)

As I pointed out in the conclusion of paragraph 1.3.3, all the proposed monosyllabic models of reading aloud, including Perry et al.'s Connectionist Dual Processing + (CDP+) model, shared the same intrinsic shortcoming: they were created to process monosyllabic words and nonwords. In order to overcome the limitations of the former models, Perry, Ziegler and Zorzi (2010) implemented an extended model, which could account for English disyllables reading; in doing so, they once again applied the nested-modeling principle, with the CDP+ model as a starting point. Indeed, the new model presented the same architecture of the CDP+ model, but included some modifications and additions; for this reason, the new model was called Connectionist Dual Processing ++ (CDP++) model (see Figure 7).



In order to be able to process disyllabic words and nonwords, the number of slots within the feature detectors, letter nodes and grapheme nodes levels was increased. Indeed, while in Perry, Ziegler and Zorzi's

Figure 8. The Connectionist Dual Processing ++ (CDP++) model of Perry, Ziegler and Zorzi (2010). From Mousikou, P., Sadat, J., Lucas, R. & Rastle, K. (2017)

(2007)

⁴¹ For further information, see Perry C., Ziegler J. C. & Zorzi M. (2014). CDP++.Italian: Modelling Sublexical and Supralephical Inconsistency in a Shallow Orthography. *PLoS One*, 9 (4).

Connectionist Dual Processing (CDP+) model each of the three levels was subdivided in 8 slots in order to process monosyllabic stimuli, in this improved version, to account for disyllables, each level includes 16 slots with the graphosyllabic and phonological templates formed by the disyllabic CCCVCCCC.CCCVCCCC structure. Another change with respect to the former version was that the lexicon was increased, so that in the lexical pathway both polysyllabic and monosyllabic words could be processed. In order to represent the mechanism of stress assignment, Perry et al. (2010) introduced two different levels. The first level is located within the sublexical pathway and consists of two stress nodes, fully connected to the graphemes and identical but independent from the phonemes; the two stress nodes have the task to make predictions about the correct position of the lexical stress. This structure allows the model to learn the relationship between graphemes and stress nodes during the training phase, in the same way as it learns the correspondence between graphemes and phonemes. The second level is placed besides the phoneme output nodes component and receives information from both the lexical and sublexical pathways. Thus, the final pronunciation of the target word or nonword is the result of the combination of phoneme output nodes and stress output nodes. Finally, in order to account for another complex phonological phenomenon which occurs in English, vowel reduction⁴², the authors added the phoneme schwa to the set of phonemes, the most frequently shortened and most frequent vowel in English.

Compared to the available empirical data, the model has shown great performance in assigning lexical stress to words. It was also tested on two nonword datasets: Rastle and Coltheart (2000) and Kelly (2004). On the first dataset, the model assigned first syllable stress on 91.6% of the stimuli and second syllable stress on 51.2% of stimuli. On the second dataset, the model assigned first syllable stress on 85.3% of the stimuli and second syllable stress on 64.3% of stimuli. It can be noted that, in the case of nonwords, the model presents the same tendency as Ševa et al.'s (2010) and Rastle and Coltheart's (2000) models to assign first syllable stress to those nonwords which were assigned second syllable stress in human readers data.⁴³

⁴² The vowel reduction phenomenon consists of a change in the way a vowel is pronounced; indeed, as a result of this phenomenon the vowel becomes acoustically weaker or reduced.

⁴³ For further information, see Perry, C., Ziegler, J. C., & Zorzi, M. (2010). Beyond single syllables: Large scale modelling of reading aloud with the Connectionist Dual Process (CDP++) model. *Cognitive Psychology*, 61. Pp 106–151.

Maintaining the same architecture and processing assumptions of the model, Perry, Ziegler and Zorzi (2014) implemented a version of the Connectionist Dual Process Model of Reading Aloud (CDP++) which could be applied to Italian words and nonwords with up to three syllables (see Fig. 8).

Italian, unlike English, is characterized by a transparent orthographic system, which means that the relationship between orthography and phonology is simple. However, Italian presents a more complex situation at the suprasegmental level, in particular regarding lexical stress: the lexical stress position within a word is not predictable neither by rules, nor orthographically. Thus, an investigation on how and when during the reading process the lexical stress is assigned is necessary for Italian as well. The Italian version of the model presents some adjustment and changes with respect to the English one, because it has to account for items with up to 3 syllables and up to 8 letters as well. The architecture of the model includes the feature detectors and letter nodes levels, each of which is divided in 8 slots; the feature detectors level can accommodate 14 features and the letter nodes level 32 letters. After an analysis of the stimulus at the letter level, the process follows the two classical routes: the lexical route and the sublexical route. The lexical route refers to the Adsett et al.'s (2009) database and

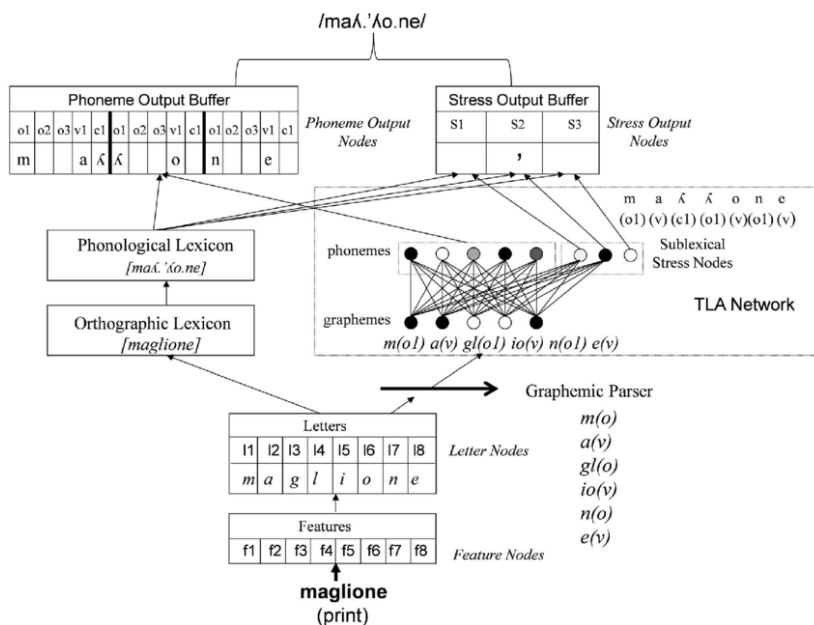


Figure 9. The Italian version of the Connectionist Dual Processing ++ (CPD++) model of Perry C., Ziegler J. C. & Zorzi M. (2014). From Perry C., Ziegler J. C. & Zorzi M. (2014). CDP++.Italian: Modelling Sublexical and Supralexical Inconsistency in a Shallow Orthography.

includes all the words with up to 3 syllables and up to 8 letters and works identically to the lexical route of the CDP++ model for English. The sublexical route, instead, involves two components: a graphemic parser and a two layer associative (TLA) network. The graphemic parser analyzes the stimulus,

divides it into graphemes and categorize the graphemes into onset, vowel, and coda categories; this categorization is used to assign the graphemes to the syllables frame and create a graphosyllabic template. Subsequently, the graphosyllabic template is processed by the TLA network, which computes the corresponding phonology and the information for the correct stress placement. The outputs of the two route converge in the phoneme output and stress output buffers where both contribute to the realization of the correct pronunciation of the item. When tested, the model showed almost flawlessly performance in reading words, but also good performance in reading nonwords. Moreover, it was shown to account for some key effects affecting the reading process, like pseudohomophone, consistency and regularity effects, and the relationship between the last two, even if it hardly accounted for the neighbourhood effect. Lastly, it demonstrated a good sensitivity to morphology, even though it does not have any morphological processing layer.⁴⁴

To conclude, the two Connectionist Dual Processing ++ (CDP++) models of Perry, Ziegler and Zorzi (2010; 2014) for English and Italian so far seem the most complete computational models to simulate the process of reading aloud single words and nonwords. Even if the models were created to compute only items with up to three syllables (for English the model works only with disyllables), excluding more complex items, their structure allows the possibility to extend the template to a multisyllabic one, with the proper modifications. However, both models still present some aspects which can be improved and, again, they let some open issues to explain, like the interaction between reading system and the broader language system and the relationship between segmental and suprasegmental level; regarding this last issue, researchers are still debating whether they dependent or independent on each other.

2.5 The bayesian approach to reading aloud

The last computational approach proposed to explain the process of lexical stress assignment in the task of reading aloud polysyllabic units of analysis is the bayesian approach. The bayesian theory was founded by Thomas Bayes (1702-1761), who started from the general assumptions that the human cognition is probabilistic in nature and that the human mind works as an estimator or a statistician that bases his/her calculations on

⁴⁴ For further information, see Perry C., Ziegler J. C. & Zorzi M. (2014). CDP++.Italian: Modelling Sublexical and Supralexical Inconsistency in a Shallow Orthography. *PLoS One*, 9 (4).

the probability of the events. The knowledge about the probability of an event is developed by a person through individual experience, from which the person learns to estimate the relative frequency of that event and the likelihood that that event happens in determined situations. This means that, when people must take rational decisions in a state of uncertainty, they rely on the observation of the world and experiences made until then to calculate the probability of a determined event to occur. Based on this information the subject makes some assumptions that can be correct or incorrect; incorrect assumptions are frequent because the calculation is usually subject to errors and biases. This process is known as the process of probabilistic inferences making.

In order to represent this theory in a mathematical form, Bayes proposed the following simple formula, called Bayes' rule (1763/1958):

$$P(h/d) = \frac{P(d/h)P(h)}{P(d)}$$

In the formula, h is the hypothesis and d is the set of data used as an evidence in the process of probabilistic inference making. This equation allows the human mind to calculate the posterior probability, $P(h/d)$, which is a value standing for the probability of the hypothesis given the data. The resulting value is obtained through the ratio between the product of the likelihood of the evidences, $P(d/h)$, which represents the probability of the observed data given the hypothesis, and the prior probability, $P(h)$, which instead represents the probability of the hypothesis before the data were observed, and the value of the overall probability of observing the data regardless of the hypothesis, $P(d)$.⁴⁵

So far, researchers have applied this probabilistic approach to the field of studies regarding human cognition in order to explain cognitive processes underlying visual perception (Feldman, 2001), object recognition (Kersten, Mamassian, & Yuille, 2004) and eye movements (Najemnik & Geisler, 2009), and some aspects of the broader language system (Chater & Manning, 2006; Norris, 2006; Norris & Kinoshita, 2008; Norris & McQueen, 2008, Xu & Tenenbaum, 2007).

⁴⁵ For more detailed information, see Bayes, T. (1763/1958). Studies in the history of probability and statistics: Thomas Bayes' essay towards solving a problem in the doctrine of chances. *Biometrika*, 45. Pp 296–315.

Regarding the process of reading aloud polysyllabic strings, this approach allows the possibility to extend the principles of the probabilistic inference to understand how the process of lexical stress assignment works. Within this framework, readers establish which is the correct position of the lexical stress by estimating the probability of each stress pattern. The bayesian approach assumes that readers start their estimation from a prior probability awareness. Building a prior probability consists in evaluating the likelihood of the occurrence of a hypothesized stress pattern within a word given some evidence. The number of the possible hypotheses concerning the position of stress coincides with the number of the syllable of the target word. Once assessed the prior probability of a certain stress pattern, readers calculate the posterior probability by comparing the prior probability of that stress pattern with the prior probability of the other possible stress pattern. The Bayes' rule can be formulated as follows:

$$P(stress/evidence) = \frac{P(evidence/stress)P(stress)}{\sum_{stress' \in STRESS} P(evidence/stress')P(stress)}$$

The prior probability of the stress pattern under consideration is given by the product of the likelihood with which evidence considered is associated with the stress pattern under consideration, $P(evidence|stress)$, and the stress pattern, $P(stress)$. In the same manner, the others stress pattern prior probabilities are calculated. The posterior probability is then calculated by dividing the prior probability of the stress pattern under consideration and the sum of the others stress patterns prior probabilities.

Two types of cues to stress can be exploited: lexical and nonlexical. Lexical evidence is based on access to orthographic and phonological representations in memory; this is a particularly useful type of evidence for high-frequency words, which are stored in the mental lexicon and get activated rapidly. Evidence from lexical access is not probabilistic, but rather deterministic, because it has perfect reliability. Since readers retrieve the lexical stress information from the mental lexicon, they are sure of which stress pattern the word require. Indeed, the resulting posterior probability measure is 1, as there are no doubts about the position of the stress. Instead, with respect to low-frequency words and nonwords the reader relies on nonlexical evidence which is

language-specific. This type of cue is detected through the analysis of the orthography of the stimulus.⁴⁶

According to the bayesian theory, the decision among different stress patterns to assign to a target polysyllabic word in reading aloud is determined by the result of Bayes' formula. If the calculated posterior probability of a certain stress pattern is high, the reader would assign that stress pattern to the target word and the higher the value the faster the response will be. On the contrary, if the calculated posterior probability of a certain stress pattern is low, the probability to assign that stress pattern to the target word is low as well and performance will slow down.

For nonword reading, a high value of the calculated posterior probability of a certain stress pattern has the effect to increase the tendency to assign that stress pattern to the stimulus among the readers. Vice versa, if the estimation produces a 50:50 ratio, the probabilities of the alternative stress pattern are similar and it becomes more difficult to choose one.

The bayesian approach to reading aloud presents three major differences with respect to the other approaches and models described so far. First, the language-specific information about the predominance of a certain stress pattern, which is therefore considered dominant, is just a starting point that establishes an initial bias to which the reader is sensitive. Indeed, in Bayes' rule, this evidence represents the prior probability of a certain stress pattern and, regardless of the precision of this information, it is an important baseline for the process of lexical stress assignment. However, this initial knowledge decreases its value as soon as evidence strongly associated with other stress patterns appears. Second, the separation between lexical and nonlexical sources of information does not reflect the existence of two different cognitive mechanisms (e.g. lexical and sublexical routes); it simply distinguishes the nature of two essentially different sources of evidence for stress, which are used by the same cognitive mechanism. Third, Bayes' rule does not need a large number of nonlexical sources of evidence for stress, because it works properly and can make accurate predictions just by using a limited number of them. All the cues the approach considers must be highly

⁴⁶ A complete description of lexical and nonlexical cues to stress will be offered in the chapter 2.

reliable, which means that the cues must be in a significant probabilistic relation with a specific stress pattern, and known to be used by the reader.⁴⁷

Jouravlev and Lupker (2014; 2015) have tested the bayesian approach validity in predicting the correct lexical stress position for Russian (see paragraph 3.1). Despite the success in simulating the performance of Russian native speakers in naming disyllabic words and nonwords and assigning lexical stress, it would be interesting to test the bayesian model for other additional languages and with stimuli of more than two syllables as well.

⁴⁷ For further information, see Jouravlev, O., & Lupker, S. J. (2015). Lexical stress assignment as a problem of probabilistic inference. *Psychonomic Bulletin & Review*.

3 Cues to stress assignment in Italian

Italian skilled readers are supposed to rely on both lexical and nonlexical sources of information to decide the correct position of the stress while reading aloud isolated polysyllabic strings of letters, such as words or nonwords. Which cues to stress are playing a role on this process and the relative importance of each cue is a matter of current investigations. To date, researchers addressing the Italian reading process have focused on three main cues to stress. First of all, word knowledge, which refers to the orthographic and phonological representations in the mental lexicon of the already-known words. This information, however, is quickly available exclusively for the processing of high frequency words. For the processing of low-frequency words and nonwords, instead, the two main nonlexical sources of information investigated are the distribution of the stress patterns within the Italian language and the stress neighbourhood information, such as its consistency and composition. Other nonlexical sources of information might play a role in the process of lexical stress assignment. For example, morphological units, such as prefixes or suffixes, the grammatical category, orthographic units, such as word endings and beginnings of different sizes, the orthographic structure of each syllable and the orthographic and phonological similarity to other existing words. Each of these cues might contribute to some extent in establishing the correct position of the lexical stress.

In this chapter, after an introducing paragraph on the important contribution of the megastudies, a large-scale investigation of the role of the several cues in lexical stress assignment will be presented. Both the relative importance of each cue and the correlations between them will be taken into account and examined. For this purpose, forty-five adults have been tested in a naming task. They were asked to read aloud a total of 800 nonwords. The resulting human behavioural data have been subsequently compared against the data coming from the simulation from the main computational model implemented to simulate the reading process in Italian, the Connectionist Dual-Processing ++ (CDP++) by Perry, Ziegler and Zorzi (2014). In this manner, it has been possible to assess the functioning and the validity of the computational model in capturing human stress assignment.

Hence, this chapter seek to shed new lights in the investigation of the factors which affect the process of reading aloud isolated polysyllabic units of analysis, and specifically lexical stress assignment in Italian, a language with variable stress pattern.

3.1 The contribution of mega-studies

In the literature regarding lexical stress assignment in free stress languages, a large variety of lexical and nonlexical sources of information proposed as cues to stress has emerged. The mainly investigated factors have been lexical knowledge, the language-specific distribution of stress patterns, some orthographic and phonological units, such as word beginnings and word endings, stress neighbourhood information, morphological units, such as prefixes and affixes, the grammatical category and information regarding the orthographic structure of the syllables. However, the investigation of these cues has often been difficult and inconclusive. Indeed, researchers could hardly detect the specific effects of the different cues in the performances and their respective roles have been confounded in many cases. For example, it is difficult to maintain separate the investigations on the individual and independent effects of suffixes and word endings and their relative role in indicating the correct lexical stress position. Hence, researchers introduced in their analysis a new approach to carry out their experiments: the megastudies. In megastudies, the several potential sources of lexical stress information can be investigated without the limitations given by the manipulation of factors in studies using a more restricted set of stimuli. Through megastudies, scientists can test a huge number of stimuli on a large number of subjects. Hence, megastudies provide a large-sized corpus of behavioural data and can increase the prograess in the reading research.

Jouravlev and Lupker (2015) were the first to investigate the combined and relative influence of the several cues to stress emerged by means of a megastudy. In their Study 5, they tested thirty four adult Russian readers in reading aloud a corpus of 500 disyllabic words submitted one at a time. Besides, they computed the posterior probabilities of each stress pattern using as prior probabilities the data retrieved in prior investigations (Jouravlev and Lupker, 2014) on the following cues to stress: the distribution of trochaic and iambic stress patterns in Russian, the orthography of the first syllable (CVC1), of the second syllable (CVC2), and of the ending of the second

syllable (VC2). Further, they compared the behavioural data against the model predictions. The results showed that the model could successfully predict the overall stress patterns in the language. Indeed, the model could compute the posterior probability of a certain stress pattern mirroring the likelihood that this word is pronounced with the predicted stress pattern by readers. Moreover, the authors noticed that the more the computed posterior probabilities to assign the alternative stress patterns similar were similar (50:50), the longer the response latencies and the higher the probability to make errors. Finally, the results showed evidence that the readers rely not only on nonlexical sources of information, but also on lexical sources of information. Within the Bayesian framework, the lexical information is deterministic, rather than probabilistic, and it has perfect validity and utility. Thus, the Bayesian model cannot predict and explain the human behaviour in stress assignment, because it cannot consider both the lexical and nonlexical information, since the lexical information is perfectly reliable alone. Thus, in order to avoid that lexical information affected the performance, in Jouravlev and Lupker's (2015) Study 6, the same procedure was applied with a sample of 200 disyllabic nonwords. Nonword items, indeed, have no lexical representation in memory, which means that the reader can rely exclusively on nonlexical sources of information in processing these units. The results suggested that the Bayesian model of stress assignment could successfully predict most of the stress patterns assigned by the readers to the presented nonwords.⁴⁸

A second megastudy on lexical stress assignment was carried out in English. Mousikou, Sadat, Lucas and Rastle (2018) tested 41 adult English readers, whose task was to read aloud a corpus of 915 disyllabic nonwords. They ran the same corpus through the three main computational models of English reading: the Connectionist Dual-Processing (CDP++) model by Perry, Ziegler and Zorzi (2010), the rule-based algorithm by Rastle and Coltheart (2000) and the distributed-connectionist network by Ševa, Monaghan and Arciuli (2009). Subsequently, the results from the behavioural analysis have been compared against those from the models simulations. First of all, the authors found by means of item-level regression analysis that the English human participants' performance was affected by the spelling-to-stress consistency of the onset and rime units in the first and the second syllables, the relative orthographic weight of

⁴⁸ For more detailed information, see Jouravlev, O., & Lupker, S. J. (2015a). Lexical stress assignment as a problem of probabilistic inference making. *Psychonomic Bulletin and Review*, 22. Pp. 1174-1192.

the two syllables, the second syllable's vowel length, the stress pattern of the item's orthographic neighbors and the certainty. With certainty, the authors meant the measure of how much the human subjects, or the computational models, are sure of the stress pattern the tested item has to receive, and they introduced it to compare the computational models certainty against the human certainty. Indeed, they calculated both the human stress certainty, as the absolute value of the difference between the percentage of people that assigned first-syllable stress and second syllable stress to each item, and the CDP++ SMA09 stress certainties, as the absolute values of the difference between the activation of the two stress nodes. Further, since Mousikou et al. (2017) noticed that some of the variables they took into account corresponded to morphological units, they concluded that morphology might play an intermediate role between sublexical orthographic units and stress, rather than having a direct influence in stress assignment, as Rastle and Coltheart (2000) claimed. Secondly, in the comparison between the models and the humans' performance, Mousikou et al. (2017) found that all the models they tested (i. e. the Connectionist Dal Process (CDP++) model by Perry, Ziegler and Zorzi (2010), Ševa, Monaghan and Arciuli's (2009) network of stress assignment (SMA09) and the rule-based algorithm (RC00) of Rastle and Coltheart (2000)) were fairly good in simulating the human data. In particular, the CDP++ predicted 81% of the human responses, the SMA09 79% and the RC00 73%. In addition, they noticed that the CDP++ and SMA09 could also capture the human certainty. Regarding the stress predictors, the CDP++ and the SMA09 approached more the human data than the RC00, supporting the idea that the statistical-learning approach, used to implement the CDP++ and SMA09 computational models, simulate better the human behaviour. Even though the CDP++ and SMA09 performance were the best in Mousikou et al.'s (2017) experiment, the two models still present some limitations, i.e. the ability to process only disyllabic units, the graphemes assignment to the different slots within the graphemic buffer and the overgeneralization of the spelling-to-sound relationship that it learns during the training phase.

Hence, by means of megastudies, researchers could make advances in two directions. First, they shed new lights both on the more specific process of lexical stress assignment and on the more general reading process. Second, they have created and provided a large database of nonword pronunciations for English. Thus, the future research can use

this resource to develop the computational models of reading and extend the research to units with more than two syllables.⁴⁹

3.2 A large-scale investigation of polysyllabic nonword reading

The present research is the first attempt to conduct a megastudy for Italian reading. We conducted a large-scale investigation of the nonlexical cues that guide skilled readers in determining the correct position of the lexical stress while reading aloud single Italian polysyllabic nonwords. From the existing reading literature we already know that stress dominance and stress neighbourhood information play a role in assigning lexical stress to nonwords (Sulpizio et al., 2013; Sulpizio and Colombo, 2013; Sulpizio, Arduino, Paizi and Burani, 2013; Sulpizio, Burani and Colombo, 2015; Arduino and Burani, 2004; Burani, Paizi and Sulpizio, 2014; Colombo, 1992; Colombo and Zevin, 2009; Colombo and Sulpizio, 2015; Colombo, Deguchi and Boureux, 2014). However, we suspect that other cues may be influential. In the literature, other attempts to test the role of the morphology and the syllable information in stress assignment process are present. Indeed, researchers claimed that, besides stress dominance and stress neighbourhood, other nonlexical sources of information have to be included in the research addressing lexical stress assignment (Spinelli, Sulpizio, Primativo and Burani, 2016; Sulpizio, Spinelli and Burani, 2017). For instance, grammatical category, word beginnings and endings of different length and orthographic syllable structure might be investigated as effective stress indicators. Spinelli, Sulpizio, Primativo and Burani (2016) made a first attempt to investigate the role of grammatical category information in lexical stress assignment, to understand whether readers are sensitive to it. Considering the distribution of stress patterns among the different grammatical categories, in Italian the percentages of words with dominant stress are higher for adverbs and nouns (95.3% and 84.9%, respectively) compared to adjectives and verbs (76.2% and 70.3%, respectively). Therefore, Spinelli et al. (2016) sought to discover whether this distribution contributes to some extent to lexical stress assignment. In Experiment 1, the authors tested adult Italian readers on a word reading aloud tasks. Subjects were presented with low-frequency nouns and verbs either isolated or within a

⁴⁹ For further information, see Mousikou, P., Sadat, J., Lucas, R., & Rastle, K. (2017). Moving beyond the monosyllable in models of skilled reading: Mega-study of disyllabic nonword reading. *Journal of Memory and Language*, 93. Pp. 169-192.

proper context. For example, when the stimulus was a noun, the context was created by the presence of an article, whereas, when it was a verb, the context was created by means of a pronoun. Results from this experiment showed that grammatical category information did not play any role in stress processing. In Experiment 2, Spinelli et al. (2016) tested the adult Italian readers on a nonword reading aloud task. They sought to assess whether the information coming from morpho-syntactic properties, such as grammatical category, gender, number or person, had a stronger effect in stress assignment compared to stress neighbourhood information. The authors created the nonwords so that the information coming from stress neighbourhood contrasted with the information provided by morpho-syntactic properties. The stimuli were presented to the subjects, again, either in isolation or within a proper context. The results showed that, when the stimuli were presented without the context, stress neighbourhood information had a greater effect. However, when the stimuli were presented in their context, readers demonstrated to rely specifically on the subset of stress neighbours with the same morpho-syntactic properties as the stimulus. For example, as Spinelli et al. (2016) predicted, the masculine singular nouns ending in *-ine* (e.g. *termine* (term) or *polline* (pollen)) received antepenultimate stress pattern most of the times when presented within their grammatical context, even though in Italian the orthographic word ending *-ine* has a consistent penultimate stress neighbourhood.

Moreover, the effect of morpho-syntactic properties was stronger for nonwords presented as verbs than for those presented as nouns. Hence, Spinelli et al. (2016) concluded that grammatical category information plays a role in lexical stress decision, at least when the stimulus is presented within a morpho-syntactic context.⁵⁰

In order to collect data regarding these variables and help the researchers interested in this topic, Spinelli, Sulpizio and Burani (2016) designed and created a lexical database, Q2Stress (Cue-ToStress). By means of this new tool, researcher can investigate not only the independent role of the different cues in the task of lexical stress assignment, but also a possible interaction among them. Moreover, the data included in

⁵⁰ For further information, see Spinelli, G., Sulpizio, S., Primativo, S. & Burani, C. (2016). Stress in context: Morpho-syntactic properties affect lexical stress assignment in reading aloud. *Frontiers in Psychology, Language Science*, 7. Pp 942.

this lexical database are divided in child-directed and adult-directed corpora and this helps to differ the investigation on adults from the investigation on children.⁵¹

Subsequently, regarding the relation between syllables and stress in reading, Sulpizio, Spinelli and Burani (2017) designed and created a new database, STRESYL. The database includes an augmented version of the PhonItalia database (Goslin et al., 2014), in which all the word forms are divided into syllables and for every syllable it is indicated in which position it occurs and whether it is stressed or not. Moreover, it contains two sets of charts listing all syllable forms and syllabic structures; the first set reports type measures and the second token measures. In both sets, all syllable forms and syllabic structures are associated with their respective data about how many times they occur as either stressed or unstressed, in number and in percentages. For example, according to STRESYL database, the syllable *ta* counts 3228 total types in the penultimate position, among which 2854 types are stressed (88%) and 374 types are unstressed (12%). Thus, one might look at how influential in assigning stress, and in reading latencies and accuracy, is the fact that a certain syllable is mostly tonic or not. As another example, according to STRESYL database, in a count based on tokens, the syllabic structure CVC occurs 531907 times in the first position, among which 293019 times is stressed (55,09%) and 238888 times is unstressed (44,91%). Thus, STRESYL database provides information about the frequency with which a certain syllable is stressed in relevant positions, such as penultimate, ultimate and first positions, either in types or in tokens. Researchers decided to start investigations on syllables, because in the reading process stimuli are assumed to be parsed in these units at the first levels of the process. Therefore, information coming from syllabic units might be useful for lexical stress assignment. Two relevant information have emerged from STRESYL. First, the majority of stressed syllables are located in the penultimate position, whereas the majority of unstressed syllables are located in the first or in the antepenultimate positions, based on a positional count. This result is in line with the distribution of the different stress patterns in Italian, which revealed that the penultimate syllable stress pattern was the dominant one. Second, some syllable forms are highly reliable for the reader in assigning lexical stress, since they have a small number of types and they in most cases, or even always, bear stress. Thus, these cues may be more effective in

⁵¹ For more detailed information, see Spinelli, G., Sulpizio, S. & Burani, C. (2016). Q2Stress: A database for multiple cues to stress assignment in Italian. *Behavior Research Methods*. Pp 1-14.

lexical stress assignment compared to the information coming from the overall stress patterns distribution. Four, the V, VC, CVCC⁵² syllabic structures revealed a strong tendency to be unstressed. All these issues about the relation between syllable and stress and the data included in STRESYL database offer a good starting point for the future research to investigate the role of the syllables in the specific process of lexical stress assignment and also in the more general process of reading.⁵³

We aimed to add new data for this investigation, by using as predictor variables six groups of variables: the stress neighbourhood information, the syllabic information with respect to stress, the affix information, the base word information, the certainty and the interactions between variables. In this regard, we made the following predictions:

1. Stress neighbourhood information: considering the existing reading literature, the consistency and composition of a stimulus stress neighbourhood has been found to influence the subjects' tendency to assign the dominant stress pattern (Sulpizio et al., 2013; Sulpizio and Colombo, 2013; Sulpizio, Arduino, Paizi and Burani, 2013; Sulpizio, Burani and Colombo, 2015; Arduino and Burani, 2004; Burani, Paizi and Sulpizio, 2014; Colombo, 1992; Colombo and Zevin, 2009; Colombo and Sulpizio, 2015; Colombo, Deguchi and Boureux, 2014). In particular, when the orthographic ending of the stimulus belongs to a large-sized stress neighbourhood mainly associated to the dominant stress pattern, the probability to assign the dominant stress pattern should increase. Vice versa, when orthographic ending of the stimulus belongs to a large-sized stress neighbourhood mainly associated to the nondominant stress pattern, the probability to assign the dominant stress pattern should decrease. Thus, we considered specifically two predictor variables measured in types. First, the number of neighbours that exhibit penultimate stress pattern. Second, the percentage of neighbours that exhibit penultimate stress pattern. We expected that the tendency to assign the dominant stress pattern increases when the nonword has a large number and high percentage of dominant stress neighbours;

2. Syllabic information: we introduced this set of predictors variables, because we have data regarding the relation between syllables and stress from the STRESYL database (Sulpizio et al., 2016). In the database, we found for each syllable the number

⁵² The letter C and V correspond to Consonant and Vowel, respectively.

⁵³ For further information, see Sulpizio S., Spinelli G. & Burani C. (2017). STRESYL. An Italian Stress-in-Syllables database for reading research. *Written Language & Literacy*, 20. Pp 80-103.

and percentages in which it bears stress within the Italian words when considered in specific positions. Hence, we sought to determine whether the information regarding the relation between lexical stress and the position of a specific syllable could influence the dominant stress pattern assignment. We took into account four variables among syllabic information. The first two are the number and percentage of word in which the nonword's penultimate syllable is in penultimate position and bears stress. The second two are the number and percentage of word in which the nonword's antepenultimate syllable is in antepenultimate position and bears stress. In particular, we expected that when the nonword penultimate syllable occurs in a large number or high percentage of words stressed in penultimate position, the tendency to assign it the lexical stress should increase. Vice versa, when the nonword antepenultimate syllable occurs in a large number or high percentage of words stressed in antepenultimate position, the probability to assign to it the lexical stress should decrease, in favour of the nondominant stress pattern. We assumed that this effect is produced by the determined characteristic of the syllable which occurs in a specific position. Therefore, this information works in a more specific level than the stress neighbourhood information. This means that, once having established the effect of the stress neighbourhood, considering which specific syllable occupy the penultimate or antepenultimate position might give additional information. For example, the nonword *bosami* ends with the final sequence *ami*, for which the stress neighbourhood information is ambiguous, indeed it has 51% penultimate stress neighbourhood and 48% antepenultimate stress neighbourhood (the remaining 1% includes ultimate and forth-from-last position). In this case, the syllabic information might be more informative. Indeed, if we consider the penultimate syllable *sa*, we find that it bears stress in penultimate position in a large number (932) and high percentage (90%) of Italian words. And if we consider the antepenultimate syllable *bo*, we find that it bears stress in antepenultimate position in a smaller number (43) and lower percentage (14%) of Italian words. Moreover, in the nonword *bosami* the antepenultimate syllable corresponds to the first syllable. Thus, we can consider also the number and percentage of Italian words in which the syllable *bo* occurs stressed in first position. Again, we find a small number (45) and low percentage (19%). Hence, for the effect of the syllabic information, we expect that the probability to assign the dominant stress pattern increases, when the syllable in penultimate position

is mainly associated to stress in that position, or decreases, when the syllable in antepenultimate position is mainly associated to stress in that position;

3. Affix information: among the different types of affixes, we decided to use specifically the suffix information.⁵⁴ We aimed to observe whether the presence of a suffix mainly associated with a dominant stress pattern increased the probability to assign the dominant stress pattern to the stimulus and, vice versa, whether the presence of a suffix mainly associated to a nondominant stress pattern decreased the probability to assign the dominant stress pattern. We sought to determine the role of suffixes and prefixes in lexical stress assignment. We expected that suffixes, besides stress neighbourhood and syllabic information, have an effect on lexical stress decision. In particular, we predicted that the presence of a suffix mainly associated to the dominant stress pattern within the nonword increases the probability of assigning the dominant stress pattern, while the presence of a suffix mainly associated to the nondominant stress pattern could decrease the probability of assigning the dominant stress pattern;

4. Base word information: nonwords may resemble to different degrees an existing word of the Italian lexicon from which it is derived. Therefore, the more the nonword resembles its base word, the more the base word information may be influential in lexical stress assignment. Specifically, we expected that when the base word is recognizable from the nonword orthographic form, the base word stress pattern affects the subject decision. When the base word has a dominant stress pattern, the probability to assign the dominant stress pattern to the nonword becomes higher, whereas, when the base word has a nondominant stress pattern, the probability to assign the dominant stress pattern to the nonword becomes lower. In addition, we included the base word mean frequency information, as we considered that the more frequent the base word, the stronger its influence in the performance. These assumptions may not agree with models, like the dual route model, which posits that words and nonwords are read via independent mechanisms, although they may be modified to account for data such as priming effects from words to nonwords (Rosson, 1983);

⁵⁴ The prefix variable have not been included in the sequential analysis, because we noticed that prefixes were atonic in most cases. Indeed, nonwords with only the prefix had 75% dominant stress neighbourhood and 25% nondominant stress neighbourhood. Therefore, we considered that a variable with such a limited variability could not be helpful in our investigations of both items that had only prefix and items that had prefix and suffix.

5. Certainty: we measured the human stress certainty in terms of the absolute value of the difference between the proportion of dominant stress assigned to each nonword and .5. So, if a nonword has a probability of .5 to receive the dominant pattern, this implies that it has the same probability to receive the non dominant pattern. The higher the difference, the greater the participant's certainty of the response. We also measure the CDP++ stress certainty, which consists of the absolute value of the difference between the activation of the stress node for the penultimate syllable within the TLA network and .5. Again, the higher the resulting value, the greater the model stress certainty of the resulting output. Considering the probability to assign the dominant stress pattern as dependent variable, we predicted that the higher the certainty that the nonword receives dominant stress pattern, the higher the probability of assigning the dominant stress pattern, and vice versa, the higher the certainty that the nonword receives nondominant stress pattern, the lower the probability of assigning the dominant stress pattern.

6. Interactions between variables: we included in this group the interaction between the base word stress information and the proportion of letters changed, because we predicted that the less letters changed the more the base word is recognizable and the stronger the effect of the base word stress pattern.

Hence, in order to investigate the effects of these variables, forty-five subjects were asked to read aloud 800 nonwords with more than two and up to five syllables. For each response, we examined in particular the participants' tendency to assign the dominant stress pattern as criterion variable, so that we could assess which are the most influential cues to stress and the existing correlations between the predictor variables we took into account. In addition, we ran a subset of the nonword corpus through the CDP++ model (Perry, Ziegler and Zorzi, 2014) and compared the results against the obtained human behavioural data. In this manner, we could evaluate the computational model adequacy in simulating the human reading isolated polysyllabic strings of letters and assigning lexical stress. Moreover, we investigated on which factors the model relies to determine the correct position of the lexical stress within the nonword stimuli and examine whether it relies on the same cues as human subjects do.

A further investigation regarded the reaction times in the human performance. We carried out a linear regression analysis in order to establish which factors have an

influence of the performance speed. We considered the following variables. First of all the length of the stimulus in letters, as in the literature the effect of this variable is shown (Juphard, Carbonnel and Valdois, 2004; Judica et al., 2002; Zoccolotti et al., 1999; Spinelli et al., 2010). Secondly, the nonword's orthographic neighbours, including the number and mean frequency of the nonword's orthographic neighbours, as the reading literature showed the effects of this variable in naming latencies (Andrews, 1989, 1992, and Sears, Hino, & Lupker, 1995, for English speakers; Peereman & Content, 1995, for French speakers; Burani and Arduino, 2004 for Italian speakers). Similarly for the base word's orthographic neighbourhood information, third, the interaction between the length and the nonword's orthographic neighbourhood, as we suspected that a large size nonword orthographic neighbourhood has the effect of speeding up the reaction times in longer stimuli responses. Fourth, the base word information, among which the base word frequency, the base word stress and the number and mean frequency of the base word's orthographic neighbours. We expected that the base word frequency has the effect of speeding up the performance. Finally, we added the variables we investigated in Study 1 and 2, stress neighbourhood information, syllable information, affix information and human certainty, in order to observe whether they have an influence on the performance latency.

3.2.1 Method

Participants

A total of forty-five Italian native speakers (9 male) took part voluntarily in the experiment. They were asked to sign a written informed consent for their participation. All of the participants were undergraduate and 24 years old on average (range [21,28]; SD = 2.8). They were right-handed, had normal or corrected-to-normal vision, and reported no reading impairments.

Materials

We used as stimuli nonwords created respecting the phonotactic constraints of Italian. Hence, we created a set of 800 nonwords by means of an algorithm implemented by one of the authors (G.S.). The algorithm selected words randomly from a subset of the Phonitalia database (Goslin, Galluzzi and Romani, 1994). All and only the Italian words

with three, four and five syllables and with more than five and up to thirteen letters were included in the subset. Moreover, the last three letters which composed the items' final orthographic sequence had a VCV or CCV⁵⁵ orthographic structure. Even if the algorithm made a random selection, the words were chosen in a weighted manner, by taking into account their frequency. For each selected base word, the algorithm reported information extracted from the Phonitalia database (Goslin et al., 1994), including the orthographic structure, the total frequency, the grammatical category and the stress pattern. Moreover, the algorithm detected the presence of an affix in the string of letters, following an orthographic criterion. It detected the orthographic units corresponding to affixes and, referring to two corpus of Italian affixes, one including prefixes and one including suffixes, established whether these were true affixes or not. For each base word the prefix and/or suffix was reported, when detected, and their allomorphs, and also the algorithm's judgment which established the authenticity of the revealed morphemes. Considering the assumption that some suffixes are mainly associated with certain stress patterns, among the base word information it was also indicated, besides the presence and the orthographic form of the suffix, if detected, the stress pattern mainly associated to it. Finally, the base word's final orthographic sequences was reported (i.e. the nucleus of the penultimate syllable and the entire last syllable) and information involving their stress neighbourhood. Hence, given the base word and all the information above mentioned, the algorithm could create up to four related nonwords.

The algorithm worked in the following way. First, one of the word letters was randomly selected in order to be replaced. The letters belonging to the word orthographic final sequence and to affixes, when detected, could not be replaced. Each selected letter was replaced by a letter in such a way that a vowel was replaced by another vowel and a consonant by another consonant. Letters were chosen randomly, but in a weighted manner, with respect to the frequency in types. As a result, the first nonword, which, therefore, consisted of the base word with one letter replaced. Subsequently, the mechanism just described was again applied to the resulting nonword to create the second nonword, to the second to create the third and to the third to create the fourth. All the letters already selected could not be selected again to be changed.

⁵⁵ The capital letters indicate vowels (V) and consonants (C).

Therefore, for each base word the algorithm could create four nonwords. Among these we selected one item to create our stimuli list.

Because we wanted our corpus to reflect as much as possible the subset of the Italian lexicon including all the words with three, four and five syllables, the distribution of morphologically complex nonwords was considered and similar portions of the morphologically complex words within the Italian lexicon were selected. Morphologically complex words and nonwords included items with only the prefix (e.g. *preordupa*), items with only the suffix (e.g. *erennelico*), items with both prefix and suffix (e.g. *rirarsi*) and items with no morphological units at all (e.g. *daguna*). The list of the nonwords is reported in Appendix A.

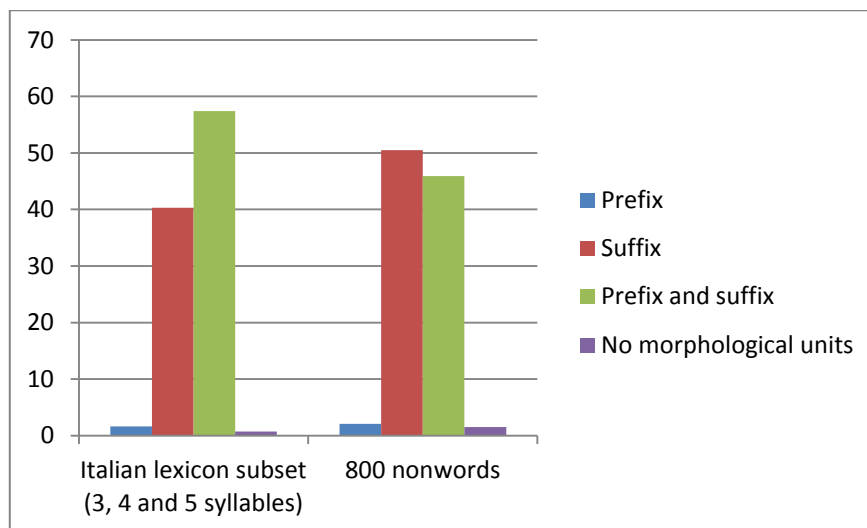


Figure 10. Percentages of morphologically complex items within the subset of the Italian lexicon including three-, four- and five-syllabic words and the corpus of 800 nonwords.

Among the 800 items, 650 ended with VCV orthographic structure and 150 ended with CCV orthographic structure. This distribution depended on the fact that the words with CCV final sequence have heavy, or close, penultimate syllable, and, as has been noted, they all bear penultimate syllable stress, with two exceptions. Therefore, we expected these items to show very little variability in the assignment of stress. However, we have been included them within the total corpus in a limited number to have and take into account such a sample of items as well.

For each base word, the algorithm created four nonwords, each with one, two, three or four changed letters. To decide which of the four nonwords to include in our corpus,

we established the criterion of maintaining similar the proportions of changed letters for words of different length (around 33%). In this manner, we aimed to reduce the possibility that the similarity of a nonword to the base word depended on the nonword's length. The proportions of changed letters for every length are reported in Table 1.

In conclusion, for each nonword we measured number of letters and syllables, number of changed letters and their positions within the string of letters, number of unchanged letters, number of the nonword's orthographic neighbour and the mean frequency of the orthographic neighbours. Moreover, we specified the orthographic structure, the syllables which compose the item, information about the relation between each syllable and lexical stress, the nature of the penultimate syllable (open vs. closed), the final orthographic sequence, the base word and its relative information, the presence of affixes and whether in the resulting nonword the affixes of the base word have been maintained and/or new affixes have been created. With this last information, we controlled whether the proportions of morphologically complex units included in our corpus respected the proportions of the same units in the Italian lexicon subset including all the words with three, four and five syllables. As a result, we found that the proportions have been approximately reproduced (see Figure 10).

Design and procedure

Participants were tested individually, in a quiet room. They were asked to seat in front of a PC screen and to read aloud the nonwords presented as stimuli. They were instructed to produce their response in a natural way, without hesitations and trying to make as few mistakes as possible, and their performance was monitored during the experimental session. The stimuli presentation and the data recording were controlled by means of DMDX software (Forster and Forster, 2003). The participants were provided with a head-worn microphone, through which the verbal responses were recorded. The list of stimuli was the same for each participant. It included ten practice nonwords, and the 800 experimental nonwords. The presentation order of the stimuli was automatically randomized in each experimental session. The 800 experimental items were divided into four blocks of 200 items each. At the end of each block it was possible to make a pause in the experiment. Each trial started with a fixation cross displayed at the center of the PC screen for 250 ms. Immediately afterwards, the

nonword stimulus appeared in the same position, in lowercase (Courier New, 12-point font), in black on a white background and remained on the screen for 2500 ms, regardless of the participant's response time. The whole session lasted approximately 45 minutes, including breaks.

3.2.2 Data preparation

The experiment generated 36000 digitized sound files (800 items * 41 participants). One of the authors (S. T.) analysed these files using CheckVocal (Protopapas, 2007). For each response the reaction time and the accuracy were recorded. The trials that presented any error in the pronunciation were phonetically transcribed and excluded from the subsequent analysis (1755 trials; 0.05% of the data). We considered errors all the missing or incomplete responses and the mispronunciations. Among the mispronunciations were included substitutions, additions, deletions or transpositions of one or more phonemes, or even syllables, responses decomposed in two or more parts (e.g. [diran] [tente] for the nonword *diratente*), false starts or the combination of more than one error in the same stimulus. The number and the percentages of errors are reported in Table 2a. The acoustic onsets of the verbal responses were hand marked. The stress judgments were made by one of the authors (S.T.). Stressed syllables have been associated with longer vowel duration, higher pitch and greater intensity than unstressed syllables (Bertinetto, 1981; Landi & Savy, 1996; McCrary, 2003; Bertinetto and Loporcaro, 2005). In Italian, the evaluation of the tonic syllable position is quite straightforward. Indeed, the most prominent syllable was easy to recognize for each response. Therefore, this procedure was made by a single author.

3.2.3 Results

With the collected data, we conducted the two following sets of analysis on the stress data, the first based on the raw data and the second based on the modal stress.

Study 1

The first set of analysis was based on the complete set of raw data. The dependent variable was the number of dominant stress productions. We used the GLMM (general linear mixed models) and made logistic regression analyses at the item level. The

variables were introduced in the model starting from those that have been supported by experimental evidence in the literature and/or following theoretical considerations. Therefore, we introduced the six groups of variables described above as predictor variables in the following order: stress neighbourhood information, syllabic information, affix information, base word information, certainty and the interaction between variables. We applied the same procedures on three sets of data: the total 36000 responses for all 800 nonwords, the responses produced using as stimuli only the items with open penultimate syllable and the responses produced using only the items with close penultimate syllable. This was done to see if the characteristics of the last syllable might vary the pattern of results. However, we noticed that almost all the items with closed penultimate syllable received the dominant stress pattern, the nature of the penultimate syllable variable masked the effects of the other variables. Therefore, we decided to consider only the sequential analysis carried out on the reduced corpus of nonwords with open penultimate syllable.

We report on Table 5 only the sequential analysis on the nonword corpus with open penultimate syllable.

In the first step we introduced the neighbourhood variables number and percentage of word neighbors with penultimate stress. As both variables were significant, we included both in the model. In contrast, for syllabic information, the only significant variable was the percentage of words in which a nonword syllable is in penultimate position and bears stress. For suffixes was significant the variable number of words including a suffix that can be associated to an antepenultimate stress pattern. In the last steps the base word stress and its interaction with the nonword length accounted for a significant proportion of the variance.

Step	Variable	Model comparison		Final model parameters			
		Chi-square	p-value	Beta	SE	z-value	p-value
Step 1		560.93	< 2.2e-16				
	nPult_ty			0.363	0.071	5.101	3.38e-07 ***
	percentPult_ty			0.967	0.083	11.662	< 2e-16 ***
Step 2		105.74	< 2.2e-16				
	percentPult_pos			0.601	0.06	9.961	2e-16 ***
Step 3		6.115	0.013				
	Suffix_s			0.157	0.069	2.274	0.02297 *
Step 4		38.977	1.756e-08				
	BWstress			0.402	0.078	5.169	2.35e-07 ***
	Prop_changed			0.107	0.055	1.939	0.05251 .
	BWstress:prop_changed			-0.180	0.055	-3.270	0.001 **

Table 5. Sequential analysis based on the raw data for open syllables only with the probability to assign the dominant stress pattern as dependent variable.

Discussion Study 1

In Study 1 we aimed to determine which factors are influential in human subject's lexical stress assignment. From the sequential analysis on this corpus, we found that seven variables in particular influence the probability to assign the dominant stress pattern in human subjects. The first two belong to the stress neighbourhood information. They indicate the number and percentage of the nonword's dominant stress neighbourhood. Thus, we concluded that the larger the number of the nonword's dominant stress neighbours and the higher the percentage of these, the higher the probability to assign the dominant stress pattern to the nonword. This assumption is in line with what researchers claimed in the former reading literature on this topic (Sulpizio et al., 2013; Sulpizio and Colombo, 2013; Sulpizio, Arduino, Paizi and Burani, 2013; Sulpizio, Burani and Colombo, 2015; Arduino and Burani, 2004; Burani, Paizi and Sulpizio, 2014; Colombo, 1992; Colombo and Zevin, 2009; Colombo and Sulpizio, 2015; Colombo, Deguchi and Boureux, 2014). The third variable whose effect

we found significant in the sequential analysis is the percentage of words in which the nonword's penultimate syllable is present stressed in penultimate position. This means, that when the nonword's penultimate syllable is present tonic in penultimate position in a high percentage of Italian words, the probability to assign the dominant stress pattern to the nonword increases. This is an additional and more specific information than that relative to stress neighbourhood, because it indicates that in the dominant stress neighbourhood, each specific syllable has a different relation with the lexical stress in that determined position and, therefore, a different degree of influence on dominant stress assignment. The presence of a suffix mainly associated to words with antepenultimate stress pattern effect consists in decreasing the probability to assign the dominant stress pattern. Therefore, we found that, besides stress neighbourhood information and the syllabic structure of the item, morphology affects the human performance in lexical stress assignment as well. The last three variables regard the base word influence. We found that the probability to assign the dominant stress pattern is higher when the base word has a dominant stress neighbourhood and lower when the base word has a nondominant stress neighbourhood. However, we also found that the base word stress pattern effect is modulated by the proportion of letters changed from the base word to the nonwords. Indeed, the fewer letters are changed, the more the nonword is similar to the base word and the stronger is the effect of the base word stress pattern. The main effect of the proportion of letters changed, instead, is not significant. Regarding the variables relative importance, we found that the stress neighbourhood information is the most significant, followed in decreasing order by certainty, interaction between certainty and syllabic information, base word stress information, syllabic information and interaction between base word stress and proportion of letters changed (see Table 4).

Study 2

The second set of analyses allowed us to compare the human performance against the computational model performance. The analysis was carried out on the items compatible with the model, as to date the model can process only the items with up to three syllables and eight letters. Therefore, we used for the comparison the smaller subset of the total corpus including only the 460 items that the model can process. The

list of the nonwords used for this analysis is reported in Appendix B. We categorized the stress patterns that the human participants assigned to each item as 1 = dominant (penultimate) and 0 = nondominant (ultimate, antepenultimate and pre-antepenultimate). We excluded from the analysis all the trials in which we could not determine which stress pattern the subject assigned or if there was an error (0,003%). We then calculated for each item the modal stress. The nonword modal stress is the stress pattern most frequently assigned by the human subjects to each nonword. Then, we ran the subset of 460 nonwords through the CDP++ model. The stress pattern assigned by the model, the activation of the TLA network for the processing of the first, second and third syllables, the number of cycles required to get the pronunciation, the phonology produced by the model, the activation of the outcome network for the processing of the first, second and third syllables were recorded. The network made different types of pronunciation errors in 24 trials; see Table 2b. All the nonwords compatible with the model received modal stress. Once calculated both the human and the CDP++ modal stress for each of the 460 items, we excluded from the analysis the items with heavy penultimate syllable (C), because they all received dominant modal stress and, therefore, the model could not be statistically estimated. Thus, the final corpus we used for the comparison between the human performance and the CDP++ model included only 380 items. Comparing the performance of the two sets of data, we found some similarities in the patterns for the human participants and the computational model. The participants assigned 78.4% of the items the dominant stress pattern (e.g. penultimate syllable stress), 21.3% of the items the antepenultimate stress pattern and 0.0001% of the nonwords received stress on the last syllable. These results reflect the distribution of the different stress patterns in the Italian lexicon fairly well. The computational model showed a strong bias toward the penultimate syllable stress as well, indeed it assigned 78.2% of the items the dominant stress pattern and 21.7% of the items the nondominant stress patterns. Thus, the model was shown to successfully capture not only the Italian distribution of stress patterns, but also the human tendency to assign the different stress patterns. In this respect, we found a high correlation between the human dominant stress assignment and the penultimate syllable TLA activation data from the CDP performance ($r = .72$; Table 3). Moreover, we calculated the rate of human certainty and of the CDP++ certainty in the nonword pronunciation,

and their correlation. We found a positive correlation between the two measures ($r = .55$; Table 3).

On these data, we carried out a sequential regression analysis, as in Study 1, with the aim of determining which factors influence the stress decisions of both the human subjects and the CDP++ on the restricted set of 380 items. We introduced in the regression analysis the six groups of variables we used in Study 1. We found significant effects of the following six predictor variables: the percentage of words belonging to the nonword's dominant stress neighbourhood, the percentage of words in which the nonword's penultimate syllable is stressed in the penultimate position, the base word stress and its interaction with the proportion of letters changed, the human certainty and its interaction with the stress neighbourhood.

We report on Table 6 the results of the sequential analysis on the nonword corpus of 380 nonwords.

Step	Variable	Model comparison		Final model parameters			
		Chi-square	p-value	Beta	SE	z-value	p-value
Step 1		163.51	<2e-16				
	percentPult_ty			2.865	0.497	5.764	8.22e-09***
Step 2		9.89	0.002				
	percentPult_pos			0.568	0.226	2.519	0.012*
Step 3		21.84	7.04e-05				
	BW_stress			0.579	0.228	2.534	0.011*
	prop_changed:BW_stress			-0.529	0.224	-2.369	0.018*
Step 4		32.96	6.975e-08				
	Certainty			2.143	0.501	4.280	1.87e-05***
	percentPult_ty:certainty			1.462	0.356	4.102	4.10e-05***

Table 6. Human sequential analysis for open syllables only with modal stress as dependent variable.

Discussion Study 2

In Study 2 we aimed to determine which factors are influential in human subject's lexical stress assignment using the restricted corpus of 380 nonwords which are compatible with the CDP++ and have open penultimate syllable. Among the first group of variables, including the stress neighbourhood information, the most influential one was the variable which indicated the proportion of words belonging to the nonword dominant stress neighbourhood. This means that the higher the proportion of words sharing the same orthographic ending of the stimulus and stressed on the penultimate syllable, the higher the stimulus probability of receiving the dominant stress pattern. Again, our results are in line with the assumptions present in the existing reading literature on this topic (Sulpizio et al., 2013; Sulpizio and Colombo, 2013; Sulpizio, Arduino, Paizi and Burani, 2013; Sulpizio, Burani and Colombo, 2015; Arduino and Burani, 2004; Burani, Paizi and Sulpizio, 2014; Colombo, 1992; Colombo and Zevin, 2009; Colombo and Sulpizio, 2015; Colombo, Deguchi and Boureux, 2014). However, in the regression analysis of Study 2 we did not find the effect of the number of words belonging to the nonword's dominant stress neighbourhood, but only the effect of the percentage of such a words. The second significant effect replicated the effect of the relation between the nonword's penultimate syllable and stress. In particular, it was found that when the penultimate syllable of the nonword is present in a high percentage of Italian words stressed and in penultimate position, the nonword's probability to receive the dominant stress pattern increases, as we found in Study 1. Regarding suffixes information, we did not find any significant effect of the presence of suffix variable. Indeed, the regression analysis showed that adding the variable suffix to the model in which stress neighbourhood and tonic syllable position were included did not account for any additional variance in the data. We expected that the presence of a suffix mainly associated with the nondominant stress pattern decreased the probability of dominant stress. However as is apparent on Table 7, the number of suffix associated with non dominant stress is small, and although the effect goes in the expected direction, it is too small to be detected by statistical analyses, as it was instead with the complete set of nonwords in Study 1.

Stress assigned	Suffix_d	Suffix_nd	Ambiguous	Not available
Nondominant	32	16	30	1
Dominant	230	11	40	20

Table 7. The contingency table between the modal stress and the presence of a suffix mainly associated with the dominant and nondominant stress patterns.

The third and fourth variables whose effects were significant in the regression analysis were the main effect of the base word stress and its interaction with the proportion of letters changed. The two variables have been found significant in Study 1 as well. Finally, the human certainty and its interaction with the stress neighbourhood. According to the first, when certainty is both high and low, also the proportion of dominant stress assigned to the nonword is high and tends to decrease when certainty is intermediate. However, this complex relation is modulated by stress neighbourhood, with certainty high also on items with a strong antepenultimate stress neighbourhood and showing a low proportion of dominant stress.

Analysis of latencies

We carried out on the same set of data a further analysis, with reaction times as dependent variable. We introduced six groups of variables within the sequential analysis one at a time. The first variable was length of the stimulus in letters, as several studies have shown an effect of letter length of both words and nonwords on latencies (Juphard, Carbonnel and Valdois, 2004; Judica et al., 2002; Zoccolotti et al., 1999; Spinelli et al., 2010). Similarly for the number of the nonword's orthographic neighbours: the fewer the orthographic neighbors, the longer are latencies (Andrews, 1989, 1992, and Sears, Hino, & Lupker, 1995, for English speakers; Peereman & Content, 1995, for French speakers; Burani and Arduino, 2004 for Italian speakers) We included also an interaction of the latter variable with length, because longer words have fewer neighbors. The base word orthographic neighbourhood and the base word stress pattern were also included. We report the results on Table 8 in the order in which they were introduced in the model.

Step	Variable	Model comparison		Final model parameters			
		Chi-square	p-value	Beta	SE	z-value	p-value
Step 1		1411.1	<2.2e-16***				
	Len			68.49	3.70	18.53	<2e-16***
Step 2		13.073	0.0003***				
	Orth_N_NW			-23.39	4.62	-5.06	5.48e-07***
Step 3		15.538	8.97e-05***				
	Len:Orth_N_NW			-19.10	4.51	-4.23	2.64e-05***
Step 4		11.863	0.0006***				
	Base_Word_Orth_N_W			-7.29	2.63	-2.77	0.006**
Step 5		9.46	0.002**				
	BWstress			-7.17	2.33	-3.08	0.002**

Table 8. Human sequential analysis based on the modal stress for open syllables only with the reaction times as dependent variable.

Discussion Analysis of latencies

Results showed that the reaction times increase when the length of the stimulus and decrease when the nonword orthographic neighbours include a large number of items. Moreover, a large size nonword orthographic neighbourhood has the effect of speeding up the reaction times in longer stimuli responses. The base word orthographic neighbourhood was also significant, although it is not clear to what extent the two factors nonword orthographic neighbourhood and baseword orthographic neighbourhood differ. Lastly, reaction times to read the nonword decrease when the base word stress pattern is dominant. No effect of either stress neighbourhood nor of syllable information was found on latencies.

Factors affecting CDP++ performance

Once established the factors which influence the human performance, we wanted to determine the cues to stress which influence the CDP++ performance. Therefore, we conducted the same set of analysis with the CDP's modal stress. We introduced

variables one at a time and in the same order as in the former analysis. We report the results on Table 9.

Step	Variable	Model comparison		Final model parameters			
		Chi-square	p-value	Beta	SE	z-value	p-value
Step 1		132.91	<2.2e-16				
	percentPult_ty			2.55	0.451	5.649	1.61e-08 ***
Step 2		27.45	1.094e-06				
	Certainty			0.262	0.169	1.555	0.12
	percentPult_ty:c ertainty			0.697	0.169	4.122	3.76e-05 ***

Table 9. CDP++ sequential analysis based on the modal stress for open syllables only with the probability to assign the dominant stress pattern as dependent variable.

Discussion Factors affecting CDP++ performance

We found that the probability to assign the dominant stress pattern by the model was significantly influenced by the size of the dominant stress neighbourhood, the CDP++ stress certainty, and their interaction. The three variables correspond to three of the variables which influence the human performance, with the difference that in the human performance we used the human certainty and in the CDP++ performance the CDP++ certainty, calculated as the absolute difference between the proportion of dominant stress assigned by the network and 0.5. However, when we added the interaction between the stress neighbourhood and the CDP++ certainty within the model, this was significant while the main effect of the certainty was no longer significant. In the analysis of CDP++ performance, the syllabic information, the base word stress pattern and the interaction between the proportion of changed letters and the base word stress pattern, which influence the human performance were not significant. In this regard, we notice that not all the base words we used to create our 380 nonwords with open penultimate syllable belong to the CDP++ lexicon, 31 are missing. Although it is unlikely that the base word information has no significant effects for this reason, we aim to carry out the same analysis in the future, excluding the items whose base words do not belong to the CDP++ lexicon.

Conclusion

The present research aimed to solve important questions within the investigation of the processing of lexical stress in Italian reading aloud of isolated string of letters. First of all, we investigated which nonlexical cues to stress the readers rely on. We asked 45 Italian skilled readers to read aloud a total of 800 nonwords, from a corpus we properly constructed. We knew from the reading literature that stress dominance and stress neighbourhood information are relevant for determining the correct position of lexical stress. However, we suspected that other factors could affect the lexical stress decision. In particular, we expected an effect of the syllables information and of some morphological affixes, such as suffixes. In addition, we supposed that the information related to the base words from which we created our nonwords could have an influence on the lexical stress decision. As a result of the analyses we conducted, we found that the nonlexical cues which influence the lexical stress assignment are not only the stress neighbourhood information, but also the base word stress pattern, its interaction with the proportion of changed letters, the rate of certainty, its interaction with the stress neighbourhood information and the syllable information. Further, we wanted to determine to which extent these variables play a role in influencing the stress assignment decision. We concluded that the most influential is the stress neighbourhood information followed in decreasing order by certainty, the interaction between the two variables, the base word stress, the syllable information and the interaction between the base word stress and the proportion of changed letters (see Table 4). Regarding the expected effects of the presence of affixes in the stimulus, we find a significant effect only in the analyses based on the complete set of nonwords. We assumed that within the restricted corpus of 380 nonwords, suffixes provide of a too limited additional information when introduced after stress neighbourhood and syllables information. Therefore, the effect of this variable could not be detected.

Secondly, we wanted to test and evaluate the performance of the Italian Connectionist Dual-Processing ++ (CDP++) computational model by Perry, Ziegler and Zorzi (2004) on the same task of reading aloud isolated nonwords. We found that the model successfully captured the human behaviour in assigning the lexical stress to these units. Indeed, the model assigned the modal stress to all the items. Specifically, it assigned 78.2% of the items the dominant stress pattern and 21.3% of the items the

nondominant stress patterns. Among the nondominant stress pattern, the model assigned the antepenultimate stress pattern in most cases. This reflects the human behaviour, because the human subjects as well assigned 78.4% of the corpus the dominant stress pattern and 21.7% the nondominant stress patterns, with a great majority of antepenultimate stress pattern among the nondominant stress patterns. Moreover, the model successfully produced the phonology of most of the stimuli. It made only 24 errors (0.05%), among which seven phoneme deletions, one phoneme substitution and sixteen unusual realizations of the intervocalic /s/. However, considering the factors which influence the model performance, we found some differences between the CDP++ performance and the human performance. We found that the model relies on the stress neighbourhood information, certainty and the interaction between these two variables. We did not find any significant effect of the base word stress pattern and the syllable information. Similarly to the results of the human performance, the analysis on the CDP++ performance did not reveal any effect of the presence of suffixes.

The present research is not conclusive, but in the present thesis we provided for a large size dataset of human responses which can be used not only by the future research to further investigate this topic and the reading research addressing the computational simulation of the reading process, but also the experts interested in the literacy education, who may use the dataset to develop new evidence-based strategies, and in the treatment of the reading disorders, as the dataset allows the possibility to distinguish and compare the typical and atypical responses.

Appendix

Appendix A - List of the 800 nonwords used as stimuli in the naming task in increasing order from the smallest to the longest item in number of letters and syllables.

Enero, ugidi, ivora, erire, asibi, evoni, ogano, olico, arore, atere, abuto, amoto ,doato, osoca, epano, omica, irizi, icola, ogore, ateri, anera, anato, voati, evane, icida, odili, isico, enito, atile, avvuse, ambumi, eltora, ascora, estolo, astica, aspare, epresi, astile, accore, ammive, purali, sonana, cinuta, ranera, ponale, bacaci, docire, nipito, cibico, sacina, parota, naroli, livili, natore, catune, lofina, tugina, denoli, demina, delisa, detaro, depono, diteva, diliso, gicore, dolani, cacina, dirati, tesere, sinete, segeva, lomata, erbero, elvola, essori, ossere, insate, fanile, fasosi, tovina, fesica, fobore, tinero, roceli, torice, dalito, rebura, pecale, ranire, larito, fanora, dobile, roguro, gerido, zilera, tireri, corare, desono, innora, incice, indaro, indaso, ampece, daguna, cotino, navora, lasoro, racale, bosami, cotata, narati, lerera, rilure, nebite, lucali, cecica, ridari, selato, rolina, lunino, ficito, ninica, ririto, mivuti, gesino, migura, tobili, genulo, ravaca, moraci, nirale, zagivi, gifore, sevica, garice, nutale, sogozi, nelico, zinile, regero, talola, intupa, astini, oggani, ostiti, pidare, mogine, panese, mareti, pirola, mavore, tadana, zunose, tacale, ropota, nipolo, culere, coseva, ducuto, poperi, tilore, rabite, sitire, rerita, rerina, relole, risami, risidi, rivori, rivase, reboso, rirela, ravano, runore, rilame, bivita, senito, satone, sinuta, sitori, satuto, tecolo, rovape, zigato, tisata, secena, rovari, soturo, sarili, semula, dasene, varito, nurato, capune, catola, raotro, ravuto, rasoro, berosi, fadore, nomica, litare, ticolo, tolale, tafela, urciso, arfici, urtima, afione, uotini, umbano, vadida, cunori, vopore, lerova, tisenno, voniva, tenivi, vanute, vibino, tigile, vamita, zepale, bodere, gutano, nolato, velumi, mocuto, alenti, aserla, ererna, naetti, ecante, isendo, elermi, nalpici, nertato, nirridi, levvone, tuntere, gispine, carrose, nelfate, cispino, raprola, conture, flamuto, probici, fostura, fampeto, mansolo, zorremo, contito, turgaci, nentina, fervato, fecrato, saccane, colbici, ninzali, sancate, cormula, nestire, narvito, ransero, bingone, moivani, rielice, angrese, toprime, terrade, mettura, niagita, tiquori, nograni, somposo, fessima, micrice, marnati, consane, mirnida, noitono, lascite, riscono, degrito, locrona, ricrito, mastati, nerdato, veprano, roncavo, pervono, gastime, nainere, niateta, liccola, zaprola, pastola, fistori, rolgice, citremo, smofica, fridoce, prerire, propili,

nuntata, dogione, rezzano, riddovo, rontico, scagino, svicena, scotico, sornato, sengito, rastimo, serbora, sormolo, sampaco, soffrole, sontesi, senfema, sastira, snetito, stapera, sforale, snovura, spivali, stecica, stisore, lupremo, steriti, tizzina, vermica, darsine, tirteno, mernore, norcido, tresato, daffate, terbano, tiprano, rorruto, vennita, varbali, nersata, naclici, vestovo, targito, betture, tarpeva, vistosa, darnice, dirersa, rirarsi, fanendo, parazzo, corerta, ergenza, esserva, sobebbe, cicanze, lopello, mametto, robesse, ercetto, atrenti, vesanti, irdetto, vorammo, tucesse, mivento, teranti, timento, renente, botelli, riretta, temalla, insorno, irbetti, reveffa, levardi, stoenfa, rinecca, cepanno, merello, leranti, tadersi, spiorete, sciolura, clispico, sempiuta, pantreso, crassita, trastico, frambese, goltione, ticchine, rettiene, corghera, rinsione, tirgione, toltrona, feggiamo, prombere, pirsipica, cirgioni, rentiamo, spitrere, stardato, scardono, scersere, scertono, sfinzura, ramplice, sfogrito, sgantero, smerlito, sbirnavo, stiemare, scencivo, sdograta, stompate, sgarvito, niltione, traccico, tamperlo, maltassi, licletto, dinnarsi, tonsello, virtasse, nirsenza, noltetta, mirfanno, rocretti, pircarti, sosmanto, seldirsi, consante, scinerto, perfersi, ristetto, sorpetto, pronessi, stufirsi, precente, nantarda, mottenti, villurno, verlezza, mardanza, stocando, stevarsi, ramporto, rembesso, spemenze, astrirci, legrende, ostresso, stapanti, patrucca, sarpenza, mengiammo, sbencarlo, rifiardo, stincarso, crellanti, cruspente, rimplessi, affirata, apperato, assusere, almevuti, autogoma, avascela, olessero, lanafico, mirivolo, lanonico, cisopere, cenipale, cipasano, canotene, citosogo, tenamica, deralivo, decoboso, detocava, detegita, degacata, dimavano, bomenica, dinacosa, escacace, etarfono, esispono, artonica, fanaloso, demareno, giracali, cegarano, detoposi, manasica, repecfici, lifitori, anirtico, illiciti, illemina, immirine, ispobili, impomito, inzadono, inserini, ingopate, insipire, larecino, romusati, lumunose, conorico, selanena, zonipola, melesimo, mepicese, riracolo, milasole, reracali, poprotiva, secarale, ralevole, opimpici, apinioni, irganici, ittevale, aspigale, essiveno, ottemuti, pinorama, riramide, panalica, poletica, pomanori, covemari, remedano, renetivo, retitore, repocata, rinavere, riganuto, rigemire, rigesoso, rotovano, ziceteli, minoforo, tatolare, umeliano, unircono, veviroso, vasevano, nelevamo, vopevano, epementi, atorezza, eritanti, enavenza, uraverso, accardini, orrersene, ersomiana, asseccere, avvarlure, ovvarnari, bovassere, cercivamo, rembevole, congerera, partelute, comivrine, pulfurali, derogione, dimontito, dinoscico, mofernere, diflobile, divingito, disantore, dirongata, vadistici, estrisivo, espririva,

encrotere, essorcene, fenticolo, firmodile, faessano, favossafi, prenerica, girotrici, biavipili, ingalnivi, infelnile, innoltere, intertoga, invungata, lascipale, laspelina, desavrato, pittefere, nefrimoni, megacrana, sotretele, manestini, carveture, istassivo, ranferoni, parlivano, nernacola, craviroso, preordupa, protitevo, progosito, renazioni, restucano, rotissevo, rinivrato, ricatravo, rifilione, rinittito, ribagrato, ravoncico, rispenapo, motebbero, scirosano, serfirici, sopribili, sottamana, sfamifure, senibiana, liscafica, sottelici, santirari, sentogere, sasceruta, sostufuto, stirnatori, stubagito, roscutare, tenintosa, mopendolo, tarcotivo, sartibili, nostivoni, crananale, effiniali, vonzitore, roginmino, nalinnari, pisazioni, saminezza, astamenti, ronavetto, selorsari, sitorassi, accurente, lotutante, diratente, vobacarsi, eccidenze, venotanza, vecomelle, mosotasse, invonetto, veditarsi, saminetta, ottirchita, confestico, chilonotri, cannartare, caltremuto, distirdere, datorsioni, ranottrice, guosandola, pessochese, randebbero, restirdere, spartusolo, scimostici, rolcendone, vargensosa, interpenti, tissodella, cirramente, premigenti, prenelando, abbigranza, rengimente, attiffante, sorramente, cempavello, disenolto, imbissendo, incatrezze, archidetto, prelapente, fronecarla, fomberanno, ringerebbe, pronissione, lescinfrato, taltiamiento, molgueranza, combrogenti, desorgiarlo, pregombari, ergontrante, scempostiamo, squingiorsela, abocazioni, accelabano, epasandosi, antimecato, anceretevi, cadelotura, depocerono, definotiva, desatidoso, elardonato, erennelico, esimarcono, intomopiva, inebolata, inospimale, intivesito, lerositori, metavecica, napaturangi, nisomopata, pamicicosi, rimapetura, semivutali, tigotudine, acalissimo, arreprativa, engerandola, consaratura, collopufali, conitugiva, contapenano, detisizioni, delamazione, metenazione, invemozzata, interlobire, instefabile, tonosatrici, pacadionali, pirlucipare, fengicolare, preneccitati, prenelovano, psicogidisi, sistipamale, virunezione, soticultura, superimento, inilottezze, cariperebbe, asteramento, vartorebbero, premirtatore, arreppotarsi, latradanza, dinellimente, allormitarsi, preancavarsi, vitudaramente, donecicretta, rassatadante, affesteranti, aggionecarsi, fennogolezzi, vesagnerebbe, orviantazione, rintrelcabili, compirzionale, contescarsene, correstardeva, diognartacato, dingiusazioni, diffonarziale, dilersuchiamo, direncrazione, prenigerviale, profistiarale, rimanquertare, rimuttrazione, assevoghiassi, prodogirmente, respicoranza.

Appendix B - Nonwords used to compare the human subjects' performance against the CDP++ model performance in increasing order from the smallest to the longest item in number of letters and syllables

Enero ugidi ivora erire asibi evoni ogano olico arore atere abuto amoto doato osoca epano omica irizi icola ogore ateri anera anato voati evane icida odili isico enito atile avvuse ambumi eltora ascora estolo astica aspare epresi astile accore ammive purali sonana cinuta ranera ponale bacaci docire nipito cibico sacina parota naroli livili natore catune lofina tugina denoli demina delisa detaro depono diteva diliso gicore dolani cacina dirati tesere sinete segeva lomata erbero elvola essori ossere insate fanile fasosi tovina fesica fobore tinero roceli torice dalito rebura pecale ranire larito fanora doBILE roguro gerido zilera tireri corare desono innora incice indaro indaso ampece daguna cotino navora lasoro racale bosami cotata narati lerera rilure nebite lucali cecica ridari selato rolina lunino ficito ninica ririto mivuti gesino migura tobili genulo ravaca moraci nirale zagivi gifore sevica garice nutale sogozi nelico zinile regero talola intupa astini oggani ostiti pidare mogine panese mareti pirola mavore tadana zunose tacale ropota nipolo culere coseva ducuto poperi tilore rabite sitire rerita rerina relole risami risidi rivori rivase reboso rirela ravano runore rilame bivita senito satone sinuta sitori satuto tecolo rovape zigato tisata secena rovari soturo sarili semula dasene varito nurato capune catola raotro ravuto rasoro berosi fadore nomica litare ticolo tolale tafela urciso arfici urtima afione uotini umbano vadida cunori vopore lerova tisenononiva tenivi vanute vibino tigile vamita zepale bodere gutano nolato velumi mocuto alenti aserla ererna naetti ecante isendo elermi nalpici nertato nirridi levvone tuntere gispine carrose nelfate cispino raprola conture flamuto probici fostura fampeto mansolo zorremo contito turgaci nentina fervato feccato saccane colbici ninzali sancate cormula nestire narvito ransero bingone angrese toprime terrade mettura niagita tiquori nograni somposo fessima micrice marnati consane mirnida lascite riscono degrito locrona ricrito mastati nerdato veprano roncavo pervono gastime niateta liccola zaprola pastola fistori rolgice citremo smofica fridoce prerire propili nuntata dogione rezzano riddovo rontico scagino svicena scotico sornato sengito rastimo serbora sormolo sampaco soffrole sontesi senfema sastira snetito stapera sforale snovura spivali stecica stisore lupremo steriti tizzina vermica darsine tirteno mernore norcido tresato daffate terbanonon tiprano rorruto

vennita varbali nersata naclici vestovo targito betture tarpeva vistosa darnice dirersa
rirarsi fanendo parazzo corerta ergenza esserva sobebbe cicanze lopello mametto
robesse ercetto atrenti vesanti irdetto vorammo tucesse mivento teranti timento renente
botelli riretta temalla insorno irbetti reveffa levardi stoenfa rinecca cepanno merello
leranti tadersi spiorete sciolura clispico sempiuta pantreso crassita trastico frambese
goltione ticchine rettiene corghera rinsione tirgione toltrona feggiamo prombere pirsipica
cirgioni rentiamo spitrere stardato scardono scersere scertono sfinzura ramplice sfogrito
sgantero smerlito sbrnava stiemare scencivo sdograta stompate sgarvito niltione
traccico tamperlo maltassi licletto dinnarsi tonsello virtasse nirsenza noltetta mirfanno
rocchetti pircarti sosmanto seldirsi consante scinerto perfersi ristetto sorpetto pronessi
stufirsi precente nantarda mottenti villurno verlezza mardanza stocando stevarsi
ramporto rembesso spemenze astrirci legrende ostresso stapanti patrucca sarpenza
rifiardo

Appendix C - Legend of abbreviations

Non_Word or NW = nonword

Base_Word or BW = base word

Sub = subject

nSub = subject's number

nNonword = nonword number

1SYLL = first syllable

2SYLL = second syllable

3SYLL = third syllable

4SYLL = fourth syllable

5SYLL = fifth syllable

PPAPULTSYLL = pre-preantepenultimate syllable

PAPULTSYLL = pre-antepenultimate syllable

APULTSYLL = antepenultimate syllable

PULTSYLL = penultimate syllable

ULTSYLL = ultimate syllable

n1SYLL_Pos = number of words in which the first syllable of the nonword occurs stressed in first position

Percent1SYLL_Pos = proportion of words in which the first syllable of the nonword occurs stressed in first position

nAPULT_Pos = number of words in which the antepenultimate syllable of the nonword occurs stressed in antepenultimate position

PercentAPULT_Pos = proportion of words in which the antepenultimate syllable of the nonword occurs stressed in antepenultimate position

nPULT_Pos = number of words in which the penultimate syllable of the nonword occurs stressed in penultimate position

PercentPULT_Pos = proportion of words in which the penultimate syllable of the nonword occurs stressed in penultimate position

OrthVCV = orthographic structure (C = consonant; V = vowel)

nSyll = syllables number

PenultSyll = penultimate syllable nature (O = open; C = close)

Len = items length in letters

Orth_N_NW = number of nonword orthographic neighbours

Orth_N_Mfreq_NW = mean frequency of the nonword orthographic neighbours

Ending = nonword final sequence

PercentPULT_Ty = proportion of words belonging to the penultimate stress neighbourhood of the nonword

PercentAPULT_Ty = proportion of words belonging to the antepenultimate stress neighbourhood of the nonword

nPULT_Ty = number of words belonging to the penultimate stress neighbourhood of the nonword

nAPULT_Ty = number of words belonging to the antepenultimate stress neighbourhood of the nonword

StressNeighborhood = stress pattern mainly associated to the nonword ending (p = piano; s = sdrucchiolo)

nLetters_Changed = number of changed letters

Base_word_FqTot = base word total frequency

Base_word_Orth_N_W = number of the base word orthographic neighbours

Base_word_Orth_N_Mfreq_W = mean frequency of the base word orthographic neighbours

BW_stress = base word stress pattern (d = dominant; n = nondominant)

Order = position in which the item has appeared within the experimental session

Accuracy = response accuracy (1 = correct; 0 = wrong)

Phonetic_tr = phonetic transcription

Stress_pattern = stress pattern assigned by the participants (p = piano; s = sdrucchiolo; t = tronco; b = bisdrucchiolo)

RT = reaction time

CDP_compatibility = item compatibility with the CDP model

CDP_stress = stress pattern assigned by the CDP model

CDP_PULT_TLA_ACT = activation of the CDP TLA network for the processing of the penultimate syllable

PHONOLOGY = the nonword phonology produced by the CDP model

1SYLL_TLA_ACT = activation of the CDP TLA network on the first syllable node

2SYLL_TLA_ACT = activation of the CDP TLA network on the second syllable node

3SYLL_TLA_ACT = activation of the CDP TLA network on the third syllable node

STRESS = Which syllable was the stress winner in (1, 2, 3) where 1 = first syllable, 2 = second syllable, 3 = third syllable. You will have to work out penultimate or antepenultimate from the number of syllables in the word. For example, with a trisyllabic word, if the stress winner is '1' it means the antepenultimate has won. If it is disyllabic, it means the penultimate has won.

1SYLL_OUT_ACT = activation of the stress output buffer in the first syllable position

2SYLL_OUT_ACT = activation of the stress output buffer in the second syllable position

3SYLL_OUT_ACT = activation of the stress output buffer in the third syllable position

LEXICALITY = whether the nonword is in the CDP lexicon

DOMINANT STRESS = whether the model assigned the dominant stress to the stimulus (1 = yes; 0 = no)

CDP_BW_lexicon = whether the base word is in the CDP lexicon⁵⁶

Modal_stress = subject's or model modal stress

⁵⁶ All the abbreviation regarding the CDP model are taken from the section ItalianCDPFaq of the CDP++ complete file by Perry, Ziegler and Zorzi (2014)

Suffix_p = suffix mainly associated with the penultimate stress pattern (p = piano)

Suffix_s = suffix mainly associated with the penultimate stress pattern (p = piano)

Prop_changed:BW_stress = interaction between the proportion of letters changed and the base word stress pattern

PercentPult_ty:certainty = interaction between the proportion of words belonging to the dominant stress neighbourhood and the certainty

Media_nLet_ch = number of letters changed in average

Por_Let_ch = proportion of letters changed

y = yes

n = no

d = dominant

nd = nondominant

p = piano

s = sdrucchiolo

t = tronco

b = bisdrucchiolo

O = open

C = close

Tables

Table 1 - Proportion of letters changed for each nonwords length in letters

Len	Media_nLet_changed	Prop_Let_changed
5	1,621	0,324
6	2,010	0,335
7	2,431	0,347
8	2,576	0,322
9	3,104	0,345
10	3,362	0,336
11	3,618	0,329
12	3,917	0,326
13	4,000	0,308

Table 2a - Subjects' errors

Error type	Number	Proportion
No response	17	0,47%
Incomplete response	159	4,42%
Substitution (one or more phonemes)	457	12,70%
Addition (one or more phonemes)	255	7,08%
Deletion (one or more phonemes)	146	4,05%
Transposition (phonemes or syllables)	120	3,33%
Decomposition	141	3,92%
False start	286	7,94%
Combination of errors	174	4,83%

Table 2b - CDP++ errors

Erros type	Number	Proportion
Phoneme deletions	7	1,52%
Phoneme substitutions	1	0,22%
Unusual realization of the intervocalic /s/	16	3%

Table 3 - Pearson's correlation for open syllables only

Variable	Len	nPUJ	Perce	nAPJ	Perce	nPUJ	Perce	nPUJ	Perce	Prop	Base	CDP	Cer	DIF	DIF	Outc
Len	1,00	-0,16	0,07	-0,46	0,06	0,10	0,04	0,08	-0,15	0,10	0,10	0,10	0,10	0,08	0,10	0,05
nPULT_Pos	-0,16	1,00	0,35	0,03	0,05	0,30	0,13	0,00	-0,11	0,11	0,11	0,11	0,14	0,09	0,11	0,15
PercentPULT_Pos	0,07	0,35	1,00	-0,03	-0,02	0,31	0,31	0,03	-0,09	0,28	0,33	0,24	0,33	0,24	0,27	0,42
nAPULT_Pos	-0,46	0,03	-0,03	1,00	0,12	-0,10	-0,05	0,00	0,03	-0,02	-0,06	0,01	-0,06	0,01	-0,01	-0,01
PercentAPULT_Pos	0,06	0,05	-0,02	0,12	1,00	-0,01	-0,01	0,06	0,03	-0,09	-0,01	-0,08	-0,01	-0,08	-0,10	-0,07
nPULT_TY	0,10	0,30	0,31	-0,10	-0,01	1,00	0,42	0,09	-0,04	0,36	0,39	0,31	0,39	0,31	0,36	0,40
PercentPULT_TY	0,04	0,13	0,31	-0,05	-0,01	0,42	1,00	0,04	0,01	0,67	0,54	0,64	0,54	0,64	0,66	0,76
Prop_changed	0,08	0,00	0,03	0,00	0,06	0,09	0,04	1,00	-0,06	0,05	0,05	0,05	0,05	0,05	0,05	0,09
Base_word_FqTot	-0,15	-0,11	-0,09	0,03	0,03	-0,04	0,01	-0,06	1,00	-0,01	-0,09	0,02	-0,01	-0,01	-0,01	-0,07
CDP_PULT_TLA_ACT	0,10	0,11	0,28	-0,02	-0,09	0,36	0,67	0,05	-0,01	1,00	0,45	0,98	1,00	0,98	1,00	0,67
Certainty	0,10	0,14	0,33	-0,06	-0,01	0,39	0,54	0,05	-0,09	0,45	1,00	0,41	0,45	0,41	0,45	0,65
DIFF_SYLL_OUT	0,08	0,09	0,24	0,01	-0,08	0,31	0,64	0,05	0,02	0,98	0,41	1,00	0,98	1,00	0,98	0,64
DIFF_SYLL_OTLA	0,10	0,11	0,27	-0,01	-0,10	0,36	0,66	0,05	-0,01	1,00	0,45	0,98	1,00	0,98	1,00	0,67
Outcome	0,05	0,15	0,42	-0,01	-0,07	0,40	0,76	0,09	-0,07	0,67	0,65	0,64	0,67	0,64	0,67	1,00

Table 4. Relative importance of the variables resulted influential in Study 1

Variables	Relative importance
PercentPult_ty	5,764
PercentPult_pos	2,519
Bwstress	2,534
Certainty	4,28
Prop_changed:Bwstress	2,369
PercentPult_ty:certainty	4,102

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