The process of stress assignment in reading aloud: Critical issues from studies on Italian.

Simone Sulpizio[1, 2], Cristina Burani[3, 4], & Lucia Colombo[5]

[1] Department of Psychology and Cognitive Science (DiPSCo), University of Trento, Italy

[2] Fondazione Marica De Vincenzi ONLUS

[3] Institute for Cognitive Sciences and Technologies (ISTC-CNR), Rome, Italy

[4] Department of Life Sciences, University of Trieste, Italy

[5] Department of General Psychology (DPG), University of Padua, Italy

Simone Sulpizio

Department of Psychology and Cognitive Science

Corso Bettini 31,

38068 Rovereto (Trento), Italy

Telephone number: (+39) 0464808667

Email: simone.sulpizio@unitn.it

Running head: STRESS ASSIGNMENT IN READING ALOUD

Word count: 6940

Abstract

In polysyllabic languages the assignment of stress is crucial for understanding the reading process. Here we review empirical evidence, drawn mainly from studies on Italian, and discuss critical issues in understanding reading. We first discuss the lexical and sub-lexical mechanisms responsible for stress assignment and propose that the former is based on item-specific knowledge and the latter on the statistical-distributional knowledge readers have acquired about their language. Then, we examine the idea that stress and phonemes pertain to two dimensions of the word, which can be placed at two different representational levels. Finally, we analyze the effects of stress assignment on word articulation, a promising field for future investigation. These issues are addressed by reviewing the studies conducted in adult and young readers to outline the developmental trajectory of stress assignment and discuss how it operates in the reading system.

Keywords: *stress assignment, reading, stress assignment development, polysyllabic languages*

Lexical stress is suprasegmental information about a word. It specifies the word's (main) stress position within the available syllabic sequence; its domain goes beyond specification of the identity of phonemes within a word (segmental phonology). Lexical stress is marked by an accentuation of syllables within a word, which in many languages become acoustically more prominent. In recent years, greater interest in lexical stress has been found in the literature on reading, particularly in languages with no fixed stress position (e.g., English, Greek and Italian). In such languages, words cannot be articulated until the stress pattern is specified, and the incorrect assignment of stress nearly always produces a pseudoword (e.g., **winDOW* instead of *WINdow* (note 1)) or a wrong word, as in the case of minimal stress pairs (e.g., *ACcent* - *acCENT;* in Italian, *anCOra* 'still' *vs ANcora* 'anchor').

In languages with a free-stress system in which stress position does not follow explicit rules, that is, in languages with a certain degree of predictability but requiring lexical consultation, the issue of lexical stress assignment is critical for understanding the processes involved in reading aloud (i.e., converting printed information into the speech signal). Prosodic information is also critical in explaining reading development and reading disabilities (e.g., Goswami, 2011) and the relationship between phonological and articulatory processes. Overall, the investigation of stress assignment in reading can provide important insights for theoretical models of reading and the issue of literacy acquisition.

Our review will consider the process of stress assignment in reading isolated words aloud. We will not, however, treat perceptual processes like spoken word segmentation. We will concentrate on the two main processing phases in reading aloud, that is, orthography-to-phonology conversion and articulation of sounds in the production stage. We will mostly consider empirical findings drawn from Italian and will discuss the issues we believe are most important: How stress information is represented and processed within a model of reading by incorporating the processes leading to articulation.

Italian is a polysyllabic language with an interesting stress system: In polysyllabic words the stress is usually on one of the last three syllables (note 2), with a predominance of penultimate syllable stress. Stress has no fixed position and is not governed by rules. The only rule in assigning stress has to do with the weight of the penultimate syllable. Heavy syllables, that is, those ending in a consonant (e.g., biSONte, bison), attract stress. Note that there are also some exceptions to the rule (e.g., MANdorla 'almond', FINferli 'chanterelles'); therefore, syllabic weight is not informative about the word's stress pattern and only lexical look-up is reliable.

The different stress patterns of Italian polysyllabic words (note 2) have different distributions in the lexicon (Thornton, Iacobini, & Burani, 1997). About 80% of the words have penultimate stress (e.g., maTIta, 'pencil'), which is the dominant pattern; 18% of the words have antepenultimate stress (TAvolo 'table') and 2% of the words have final stress (e.g., coliBRÌ, 'hummingbird'). Only final stress is graphically marked. At the acoustic level, stress affects the phonetic realization of segments. No vowel reduction is present in Italian; however, a stressed vowel is characterized by higher amplitude and duration than an unstressed one (Bertinetto, 1980; Sulpizio & McQueen, 2012;).

How is primary stress assigned in reading?

The issue of stress assignment has been addressed in the reading literature since the early 90's (Brown, Lupker, & Colombo, 1994; Colombo, 1991; Colombo & Tabossi, 1992). In her seminal study Colombo (1992) argued that in Italian lexical knowledge is an important factor in assigning stress to polysyllabic words. This claim was based on the frequency by stress type interaction found in a reading aloud task: High frequency words had fast access to learned pronunciations, whereas low frequency words were more likely to be affected by other concomitant factors, like stress regularity. Results in line with this view have been obtained in other free-stress languages, such as English, in which a stress type by word

frequency interaction similar to that of Colombo (1992) was reported (Rastle & Coltheart, 2000), and Greek, in which it was shown that in assigning stress to nonwords the resemblance that stimuli have with real words strongly affects stress assignment (Protopapas, Gerakaki, & Alexandri, 2007).

Lexical-phonological knowledge about stress may work fine with known words. However, people also read words they have never encountered before. How is this process accomplished? How is it different from assigning stress to words? One answer to this question proposed in the literature is that a kind of "rule" applies. For instance, Rastle and Coltheart (2000) found that stress assignment to pseudowords (or new words) occurs sub-lexically through the application of a set of rules. The authors assumed that the sublexical route identifies the most common stress pattern in a language as the regular one and assigns it by default (Brown et al., 1994). Besides this "regularity principle" the authors suggested that the sub-lexical route carries out a morphological look-up of the orthographic sequence by consulting an affix store: Some affixes are associated with a certain stress pattern (e.g., the suffix -ness is associated with trochaic stress) and thus operate as stress markers.

The idea of a general rule to assign stress is also present in the speech production literature. Reading aloud not only requires the activation of phonological representations, but also their actual phonetic and articulatory realizations. Thus, speech production and reading share the latest stages (i.e., phonological and phonetic encoding) and the mechanisms operating in the two processes might be common to both (Colombo & Zevin, 2009; Roelofs, 2004; on this issue, see also the sections below). In Levelt, Roelofs and Meyer's (1999) model stress information is accessed and used by the system during the phonological encoding of a word, when segmental information and metrical information are retrieved in parallel and independently. Stress is specified through a metrical frame in which syllable position is defined. During the segment-to-frame association, segmental information is combined to suprasegmental (metrical) information through an incremental process that inserts segments into slots

made available by the metrical frame. The resulting phonological word is thus used for phonetic implementation of the stimulus. In the model, the most frequent (dominant) stress in a language is assigned by means of a default rule, whereas for words with irregular (non-dominant) stress, this information is retrieved from the lexical entry.

Over the years, the idea of a rule-based sub-lexical system for stress assignment has been replaced in the reading literature by a perspective that considers this process as probabilistic, in line with a statistical learning approach. In this framework there is no "regularity" and there are no rules; readers assign stress based on distributional information they extract from the lexicon and specifically from connections between orthographic and phonemic units (Arciuli & Cupples, 2006; Burani & Arduino, 2004; Colombo, 1992; Jouravlev & Lupker, 2014; Kelly, Morris, & Verrekia, 1998; Sulpizio, Arduino, Paizi, & Burani, 2013). Two main factors have been shown to influence stress assignment in reading within a statistical learning approach: a) the overall distribution of stress patterns in a language (stress dominance or typicality); b) the sensitivity of speakers to the statistical covariation of segmental patterns and stress (stress neighborhood consistency).

Stress pattern distribution and the assignment of stress.

The distribution of different stress patterns varies from language to language depending on phonological and grammatical factors. For example, in English disyllabic words initial stress is the most typical pattern overall. However, verbs most frequently show final stress and nouns, initial stress. Similarly, in Russian there are different stress distributions for disyllabic nouns, verbs and adjectives: adjectives are more likely to be stressed on the first syllable, whereas verbs and nouns have a more balanced distribution of stress on the two syllables (Jouravlev & Lupker, 2014).

Although no explicit information about the relative distribution of the different stress patterns is

taught, speakers implicitly learn this information. The fact that different patterns are distributed differently supports the idea that the phonemic system is biased toward the most frequent stress pattern (Arciuli & Cupples, 2006; Arciuli, Monaghan, & Ševa, 2010; Jouravlev & Lupker, 2014; Lukatela & Turvey, 1990; Perry, Ziegler, & Zorzi, 2010).

As noted, Italian accentual patterns have different distributions in the lexicon, with most words bearing penultimate stress and apparently unaffected by grammatical class. Studies investigating the role of overall stress distribution in Italian have provided contrasting results. Colombo (1992; Colombo & Tabossi, 1992) found an advantage for words with the most frequent stress pattern, but only when they were of low frequency. By contrast, Burani and Arduino (2004) found no advantage for dominant stress words. Other investigations also failed to report this effect, showing no (or a very weak) difference in the processing of the two stress patterns (Colombo & Zevin, 2009; Sulpizio, Job, & Burani, 2012b). Thus, evidence suggests that in Italian adults' reading general distributional information does not have a strong role in assigning stress to words.

Statistical covariation of orthography and phonology.

A second source of information for stress in reading comes from frequent connections between orthographic units and corresponding phonological units. Colombo (1992) proposed the notion of stress neighborhood, that is, the proportion of words that share the stress pattern and the orthographic/phonemic sequence. For example, the final sequence -ola is associated with antepenultimate stress, because it occurs predominantly in three-syllabic words like PENtola, ('pot'), which have antepenultimate stress. Thus, words ending in –ola and having antepenultimate stress (PICcola) are consistent with their stress neighborhood. By contrast, words with the same ending and penultimate stress (piSTOla) are inconsistent. The sequence -ato is almost always included in words

with stress on the penultimate syllable, such as geLAto (ice cream), and is therefore consistent. Stress neighborhood consistency may provide cues about stress and be actively exploited by readers. Several studies have verified its influence in reading Italian words and pseudowords with stress consistent items named faster and more accurately than inconsistent ones (Burani & Arduino, 2004; Burani, Paizi, & Sulpizio, 2014; Colombo, 1992; Colombo, Deguchi, & Boureux, 2014; Colombo & Zevin, 2009; Sulpizio et al., 2013; Sulpizio & Colombo, 2013).

Stress neighborhood, as formulated by Colombo for Italian (1992), is based on the last syllable plus the nucleus of the penultimate one, that is, the rhyme. Whether the rhyme includes primary stress or not will inform the assignment of primary stress in words and nonwords. The idea that rhymes are important units for stress is present also in the English literature (e.g., Chomsky & Halle, 1968). However, some authors argue that both the initial and the final letters in words may be important predictors of stress, and that these units may differ in size because stress may be indicated by a single letter as well as by a group of three or four letters (see Monaghan, Arciuli, & Ševa in press).

Several studies have shown that in pseudoword (or in very low-frequency word) reading, both stress dominance and stress neighborhood contribute to some extent. Colombo (1992) constructed pseudowords with endings that belonged to stress neighborhoods with stress on either the penultimate or antepenultimate syllable and found that the proportion of antepenultimate stress assigned to pseudowords depended linearly on the number of words that shared (antepenultimate) stress, with a strong correlation between the two variables ($r = .75$). Further confirmation comes from Colombo and Zevin (2009) who found that pseudoword primes constructed with final sequences belonging to strongly consistent neighborhoods were assigned stress consistent with the neighborhood. Sulpizio and colleagues (2013) also showed that readers tended to assign stress according to the pseudowords' final sequence and not to stress dominance. For example, *pumbola* mostly received antepenultimate stress

because its final sequence primarily occurs in words with antepenultimate stress.

The use of statistical information to assign stress is not a language-specific property. Studies in English (Arciuli & Cupples, 2006; 2007; Arciuli et al., 2010; Kelly et al., 1998), Greek (Protopapas et al., 2007) and Russian (Jouravlev & Lupker, 2014) have shown that distributional information on the overall relative frequency of stress pattern types is a powerful source of stress assignment also in these languages. These studies have also shown that (like in Italian) different factors are influential in assigning stress to a stimulus, including orthographic cues, stress dominance, and for some languages, grammatical class (note 3). For instance, Jouravlev and Lupker (2014) found both an effect of stress regularity (dominance) and orthographic cues to stress in adjectives, a category with asymmetrical stress patterns. Empirical investigations in English showed both an effect of stress typicality (Arciuli & Cupples, 2006) and orthographic cues to stress not only from word endings but also from word beginnings (Arciuli et al., 2010; Kelly, 2004). Recent support also comes from a study that investigated probabilistic orthographic cues to stress in six languages (English, Italian, Greek, Spanish, German and Dutch; Monaghan et al., in press): The authors found that in all languages both word endings and word beginnings could be reliable sources of information about stress assignment.

In sum, evidence from both word and pseudoword reading suggests an effect of orthographic information on stress assignment, which involves a sublexical mechanism converting strings of graphemes into the corresponding phonemes. This mechanism is implemented by models that simulate print-to-sound conversion through a connectionist network (Pagliuca & Monaghan, 2010; Perry, Ziegler, & Zorzi, 2014).

Stress assignment in young readers.

Successful reading development is based (among other things) on good phonological awareness, i.e.,

sensitivity in perceiving and operating on the phonological segmental and suprasegmental properties of words and nonwords (see, e.g., Goswami, 2011; Holliman, Williams, Mundy, Wood, Hart, & Waldron, 2014; Holliman, Wood, & Sheehy, 2010). Therefore, studying how the process of stress assignment develops is important for understanding the developmental trajectory of the reading system and can also help identify difficulties in reading development.

Children with different reading abilities may use different sources of information for assigning stress. Sulpizio and Colombo (2013) tested second and fourth grade Italian children in a reading aloud experiment with words and pseudowords by manipulating stress dominance and word frequency while they controlled stress neighborhood. Younger readers showed a more pronounced bias toward assigning dominant stress than older readers. For example, second graders made a large number of stress errors when reading low-frequency non-dominant (antepenultimate) stress words (e.g., *aNIma instead of Anima, 'soul'). With increasing age, children tended to assign stress by relying on stress neighborhood, with a decline in the effect of stress dominance. Burani and colleagues (2014) further strengthened this conclusion in a study in which they tested Italian fourth graders reading aloud low-frequency words. The authors orthogonally manipulated stress dominance and stress neighborhood and reported effects of stress neighborhood on both reading times and stress errors: Fourth-graders were faster and more accurate when reading words with a consistent than an inconsistent stress neighborhood but showed no effect of stress dominance.

These data suggest that the developmental trajectory of distributional knowledge goes from the more general bias favoring dominant stress to a specific reliance on stress neighborhood, which develops quite fast (at least in Italian) and becomes the preferred source of information for stress assignment when sufficiently strong cues are available. An explanation of this trajectory can be found in lexical development: In younger children, the lexicon (in particular the orthographic lexicon) is still

limited. Thus, younger readers have neither acquired sufficient knowledge about a word's stress neighbourhood nor have they strongly consolidated orthography-to-phonology lexical and sub-lexical connections. Consequently, younger readers may be prone to using the more general and earlier available distributional knowledge from speaking and listening (i.e., stress-dominance). As reading skills improve, readers abandon the bias for the dominant stress and start using more specific distributional information (stress neighborhood). Note that a similar developmental trajectory of stress assignment has been reported in English: The stress-dominance bias affects younger but not older English-speaking readers who rely more on orthographic cues to stress (Arciuli et al., 2010).

The developmental trajectory of stress assignment was simulated by the computational model proposed by Arciuli and colleagues (2010). The model, implemented for English, is a single-way connectionist network able to map orthography onto stress position. The authors showed that the model (a) was able to discover the distributional information concerning stress driven by the orthographic input and (b) had a performance similar to that of English-speaking children learning to read (i.e., a bias toward the dominant stress in beginning readers followed by an increasing tendency to assign stress on the basis of word endings). These findings show that an approach based on the acquisition of statistical information may describe the development of stress assignment in reading quite well.

Can suprasegmental and segmental representations be separately accessed in reading?

One issue that has important implications for the nature of stress representation is whether segmental information is represented and processed independently of the accentuation pattern. Lexical stress is suprasegmental information, which specifies the word's (main) stress position within the syllabic sequence, and its domain goes beyond specifying the identity of phonemes within a word (segmental phonology). The independence of suprasegmental information from segmental information is widely

accepted in linguistics and in some psycholinguistic theories, which assume that phonemic segments and stress refer to different abstract levels of representation (e.g., Hayes, 1995; Nespor & Vogel, 1986). As highlighted above, Levelt et al.'s (1999) model of speech production assumes that in stress languages segmental information and suprasegmental/metrical information of a word are accessed separately and in parallel by two different mechanisms after lexical selection. The outputs of these mechanisms are then combined as inputs to the articulatory program. Note that the architecture proposed by Levelt and colleagues (1999) has been recently extended to non Indo-European languages, in particular, Chinese and Japanese (Roelofs, in press).

The claim that segmental information and suprasegmental information are accessed and/or computed separately received its first empirical suppport from the neuropsychological literature (Cappa, Nespor, Ielasi, & Miozzo, 1997; Laganaro, Vacheresse, & Frauenfelder, 2002; Miceli & Caramazza, 1992). Cappa and colleagues reported the case of an aphasic patient (with a lesion involving the left temporo-parietal cortex) who made many stress errors when producing words with unpredictable stress (e.g., foTOgrafo 'photographer'→*fotoGRAfo). The patient was able to retrieve and/or compute the correct segments of the word, but in many cases not its metrical frame, in particular when low-frequency words with the less frequent stress pattern were involved.

Most evidence supporting the independence of segmental and suprasegmental information comes from speech production tasks. The processes of speech production and reading aloud partially overlap and possibly share the latest stages (i.e., phonological and phonetic encoding; Colombo & Zevin, 2009; Roelofs, 2004). However, there may be important differences between the two processes. In particular, while speech production following conceptual input is always lexically mediated, reading can be the result of an orthography-to-phonology conversion procedure and may be carried out at a sublexical level and, thus, not involve either semantics or the lexicon (e.g., Coltheart, Rastle, Perry,

Langdon, & Ziegler, 2001; Seidenberg & McClelland, 1989). Thus, a possible difference between conceptually driven production and reading aloud may depend on whether the phonological lexicon is accessed. For example, the activation of phonological segments might occur holistically when lexically mediated and serially when the grapheme-to phoneme conversion process is involved (Coltheart et al., 2001).

To test whether suprasegmental information is dissociable from segmental information in reading, Colombo and Zevin (2009) used a "pathway priming" methodology, reasoning that if stress is represented independently of segments it should be possible to obtain priming of the metric structure only. A sequence of five primes preceded a target and all stimuli, both primes and targets, were read aloud. The five primes always had the same stress, and the target did or did not share the stress pattern with the primes; there was minimal prime-target similarity at the segmental level. By varying the lexical nature of the primes, the authors tested stress computation within either a lexical context (word primes, e.g., CELtica, ALluce, PROdigo, LAmina, ZINgaro, *SUDdito,* 'celtique, big toe, profligate, laminate, gypsy, subject') or a sublexical context (pseudoword primes, e.g., lisico, astola, parico, ballido, vimbolo). The inclusion of sequences of prime pseudowords is important because while in production tasks lexical access always follows lexical selection, pseudowords and low-frequency regular words can be read via a non-lexical mechanism. Colombo and Zevin (2009) found that metrical representation could be primed (when primes and targets shared the stress pattern) but only with pseudoword primes. The same pattern of results emerged for both penultimate (dominant) and antepenultimate (non-dominant) stress targets. These results suggest that in reading aloud the process of stress assignment is separable from segment computation. However, they also indicate that stress priming can be induced only when sublexical processing is emphasized.

Sulpizio and colleagues (2012b) examined whether the separate computation of word stress

might also occur in the context of lexical reading. The authors presented only word pairs with the same or a different stress pattern (e.g., TESsera – BUfala, 'card' – 'hoax' *vs*. cuGIno – BUfala, 'cousin' – 'hoax'), thus emphasizing lexical processing, and found that participants were faster in reading targets preceded by a congruent-stress prime than those preceded by an incongruent-stress prime. The results were identical for penultimate (dominant) stress and antepenultimate (non-dominant) stress targets (cf. Sulpizio & Job, 2013). These findings suggest that priming occurs also when reading through a lexical procedure (all stimuli were words).

Evidence of the effect of a priming context in reading has been reported also in Serbo-Croatian, a language whose orthography has characteristics similar to Italian, with very transparent grapheme-phoneme correspondence but unpredictable stress, and in which the dominant accentuation is on the antepenultimate syllable (Lukatela & Turvey, 1990). Priming a word like maŠIna (machine), stressed on the penultimate syllable, with a word like MAlina (raspberry), stressed on the antepenultimate syllable, yielded no phonemic similarity advantage . By contrast, an advantage appeared when stress was not an issue, that is, with lists of disyllabic words stressed only on the penultimate syllable. The authors concluded that the effect of stress incongruence was stronger than the effect of phonemic similarity, thus bringing about a null effect. In their account, Lukatela and Turvey (1990) assume that stress is specified at the level of articulatory units, which are connected to the layer of output phoneme units and word units that are only activated in reading aloud tasks (and not, e.g., in lexical decision). Thus, in the example pair MAlina-maŠIna, the phoneme /a/ would be activated at the phonemic level for both words, while at the articulatory level different units would be activated in second position: a long, rising /a/ for the prime and a short rising /a/ for the target, which thus inhibit each other. This interpretation in terms of inhibition suggests that priming effects are not necessarily evidence of an abstract representation of stress in the way conceived, for example, by Levelt and collaborators, in

which metrical and segmental information are completely independent.

A different perspective was assumed in Pagliuca and Monaghan's (2010) connectionist model, in which stress information was implemented as an additional feature to each vowel phoneme, thus modifying the preceding vowel while specifying its prosodic characteristics. Although this computational choice did not prevent the model from learning to abstract and generalize information, it certainly made learning more difficult. Indeed, the model was able to simulate most effects found in the literature, with very few parameter assumptions.

As noted, prosodic priming effects can be interpreted in terms of a separate representation of stress, but studies of speech production (Roelofs & Meyer, 1998; Schiller, Fikkert, & Levelt, 2004) did not find evidence of pure metrical priming. However, word reading could be more permeable than speech production to a purely metrical priming effect because of differences in the way metrical and segmental information are processed. In speech production, both types of information need to be retrieved from memory. By contrast, in reading aloud metrical information needs memory retrieval, whereas phonological segments are activated through orthography-to-phonology conversion, and this process can be refreshed from the visual input (see, e.g., Bates, Burani, D'Amico, & Barca, 2001; Janssen & Domhas, 2008). Moreover, metrical structure may be available in reading with different timing compared to segmental information, in particular when reading involves sublexical processing (i.e., when pseudowords are presented as primes: Colombo & Zevin, 2009) and/or when the reader is exposed to a transparent orthography, in which orthography-to-segmental phonology conversion is very fast because it is regular (Paulesu et al., 2000).

Note also that metrical priming likely involves processing abilities that are not present in young children. In the study by Colombo et al. (2014), carried out with the same paradigm as Colombo and Zevin (2009), second-grade Italian children showed priming only for pseudoword targets with weak or

inconsistent neighborhoods (i.e., with stress not straightforwardly derivable from orthography), and were more affected by the dominant stress pattern of the language. These findings suggest that sensitivity to priming is based on a mechanism of on-line exploitation of the metrical structure of the prime that is not yet available to younger children, perhaps because of memory limitations (see also Sulpizio et al., 2012a). The results also suggest that an abstract metrical frame does not constitute the basic way of stress representation and processing. This is shown by the fact that in reading aloud children are able to assign stress to stimuli but are unable to manage stress information independently of segmental information.

Further evidence in support of this view comes from stress neighborhood effects (Burani & Arduino, 2004; Colombo, 1992). As suggested above, stress neighborhood effects show that segmental information about the *final* part of the word influences the location of stress; thus, these effects may be incompatible with the notion of complete autonomy or separation of the two types of information. This is because two identical orthographic sequences (-ica in TRAgica and forMIca) are phonetically different when one is stressed and the other is not. Support for the view that segmental and suprasegmental information may not be entirely separate comes also from neuropsychological studies in aphasic patients, which show that segmental errors are less likely on unstressed syllables and on the syllable carrying the most typical stress pattern in the language spoken by the patient (Howard & Smith, 2002; Laganaro et al., 2002). Given this contrasting evidence, we have to conclude that segmental and suprasegmental information can be managed separately by the reading system, but the separation of the two types of information may only hold under specific conditions.

The empirical findings reviewed here show that priming effects occur within both lexical and sub-lexical processing, suggesting that both mechanisms are linked to the stress sub-system and may cooperate at some level of the reading system in which the phonological outputs of both routes

converge. A similar architecture was proposed by Perry and colleagues in their CDP++ model (2010; 2014), which considers the stress sub-system as a component of the phonological output buffer, separate from the phoneme sub-system. The Italian version of the model, CDP++ Italian (Perry et al., 2014), can simulate the reported stress priming effects: The prime modulates activation within the stress sub-system, either facilitating or interfering with the assignment of stress. In any case, the model lacks a specification of how stress and segments are fully integrated in a phonological word in order to drive motor implementation. At least two computational solutions are possible: a) stress is applied as an abstract specification on a phonemic sequence that is syllabically organized (such as the phonemic sub-system of the CDP++); b) similarly to what was claimed by Levelt et al. (1999) for speech production, phonemes are inserted into a metrical frame containing information about the number of syllables and stress position. However, the current data do not allow to adjudicate between the two possibilities.

Does stress assignment affect articulation?

Sulpizio and colleagues (2013) investigated how the timing of articulation planning interacts with stress position. Italian adults were faster at reading pseudowords with antepenultimate (non-dominant, e.g., VOsora) than penultimate (dominant, e.g., voSOra) stress. They interpreted the results in terms of the units involved in planning articulation. During articulatory planning of the phonological unit readers can buffer a partial articulatory representation of the stimulus, which includes its initial part up to the stressed syllable (cf. Sternberg, Knoll, Monsell, & Wright, 1998; Sulpizio & Burani, in press). The proposal is based on the idea that articulation cannot start until the stressed syllable is phonetically planned, because stress affects the coarticulation properties of phonemes and the phonetic realization of syllables and organizes the rhythmic structure of the word. When participants read polysyllabic pseudowords, the mapping from phonetics to articulation may vary according to the stress position, , with pseudowords assigned antepenultimate stress requiring articulatory planning of a smaller portion

than pseudowords assigned penultimate stress (one vs. two syllables in three-syllable pseudowords, respectively). In this view, the two stress patterns require a different number of units to be buffered (Levelt, 1989), and the time needed to retrieve the articulatory program for antepenultimate stress stimuli will be shorter than that needed for penultimate stress stimuli. The tendency to start articulatory planning of the pseudoword before its full phonetic encoding might be more pronounced with longer polysyllabic stimuli. In the case of pseudowords with few syllables, instead, the reading system might behave as it does for monosyllables, with articulation starting when the stimulus has been completely encoded (Rastle, Harrington, Coltheart, & Palethorpe, 2000).

The difference between antepenultimate- and penultimate-stress stimuli is difficult to detect with real words. The literature on Italian words reports few and puzzling results, because every possible pattern has been found (i.e., advantage for antepenultimate-stress words: Burani & Arduino, 2004, Experiment 2; advantage for penultimate-stress words: Colombo, 1992; no difference between penultimate- and antepenultimate-stress words: Burani et al., 2014).

Therefore, considering the available data it can be assumed that articulatory planning proceeds differently depending on whether the stimuli are words or nonwords. In the case of words, the lexical-phonological representation activates complex articulatory programs that span the whole unit. Participants retrieve a phonetically-detailed representation of the stimulus, because they have already articulated the sequence several times. In the case of nonwords, having to assemble a phonological/phonetic representation never articulated before, the system might use a rightward incremental procedure that assembles the stimulus' phonetic shape one syllable at a time. The incremental procedure is similar to the way in which, according to Levelt et al. (1999), the speech production system works during phonetic encoding. However, speech production and reading aloud may differ as to the timing of articulation: in the former case articulation starts only when all syllables

are phonetically encoded, as claimed in the most prominent theory of speech production (Levelt et al., 1999; but see, e.g., Meyer, Roelofs, & Levelt, 2003 for a more flexible approach). Differently, empirical findings in Italian suggest that in reading articulation may start as soon as the material up to the stressed unit has been encoded. For example, Sulpizio and colleagues (2013) found that readers were faster at reading pseudowords with antepenultimate (non-dominant, e.g., VOsora) than penultimate (dominant, e.g., voSOra) stress. Thus, the articulation of the nonword voSOra, may start as soon as the segment voSO has been encoded, whereas for the nonword VOsora, the encoding of VO will be sufficient to release the articulation.

The difference between reading and speech production might be either task- or language-specific. In reading aloud linguistic input is constantly under the reader's eyes, and the system has the chance to refresh and/or update the active information throughout the reading process. Thus, there is no theoretical reason to wait for the end of phonetic encoding, because this process can be completed after articulation has started. With regard to differences among languages, the flexibility of the size of the articulation unit might depend on the transparency of the syllable boundaries: in Dutch, for example, the syllable boundaries are transparent, whereas in English they are not. Languages with opaque boundaries might lead to less chunking into syllables and induce recourse to larger planning units than those with transparent ones (Cholin, Dell, & Levelt, 2011).

Future directions

Stress and phonetic representation.

How the reading system converts an abstract phonological representation into a motor program ready for articulation is far from being understood and computational models are silent on this. The idea that stress is represented as an abstract phonological representation separately from phonemes (e.g., Cappa et al., 1997; Sulpizio et al., 2012b) implies that at some point during the reading process segmental and

suprasegmental information have to be assembled together and the phonological word has to be converted into a phonetically detailed representation serving as input to articulation. Within this process the suprasegmental level modifies the segmental one, with the former specifying some of the phonetic properties of the latter for its correct realization (see, e.g., Cutler, 2005). To illustrate, consider the English orthographic sequence <object>: The assignment of stress to the second syllable shapes its phonetic realization as [əb'dʒɛkt], with a *schwa* sound in the first position and a full stressed vowel in the second syllable; differently, with stress on the first syllable, the orthographic sequence is phonetically realized as ['ɒbdʒɪkt], with two full vowels; the former is more prominent (longer and higher in pitch) than the latter. Note that also in languages with no vowel reduction, like Italian, stressed syllables are acoustically different from unstressed ones.

The interplay between segmental and suprasegmental material appears to be a crucial aspect of polysyllabic word reading. To understand how it works, two issues should be investigated: a) the relative timing of activation of segmental and suprasegmental information; b) how the two types of information are assembled together. These issues are neglected by all models of polysyllabic word reading (Pagliuca & Monaghan, 2010; Perry et al., 2014), which do not describe such processes nor those needed for the retrieval and implementation of motor programs.

In a dual-route perspective similar to that of the CDP.++Italian, in the case of high-frequency words, which are retrieved through lexical look-up, the retrieval of stress and phonemes from lexical phonology could have a similar time course. In a similar way, in the case of nonwords, the time course of sub-lexical computation could be similar for stress and segments. However, for low-frequency words, both routes are highly involved, with the lexical one proceeding slowly.In this case, segmental material might be processed faster than suprasegmental one, because the retrieval of segmental information may proceed faster in sublexical than lexical reading (i.e., because Italian is a highly

transparent language). Consequently, when the phonemes of the word are active the information about stress might not yet be available, because most often it can only be correctly specified through lexical look-up. This would imply a delay in stress-to-segment integration, which needs both types of information in order to take place. In this view the locus of stress-to-segment integration might be the phonological output buffer, in which both the output of the operation of stress assignment within the metrical frame and the output of the sublexical spelling-sound conversion converge. Thus, we would need to assume the existence of a further stage of processing in which an articulatory buffer maps the results of the integration into a phonetic realization. In this perspective, however, we have to be prepared to complicate the theory and add a further box to the reading system.

Differently from the preceding account, one might assume that a fast phonology-to-phonetic transcoding procedure operates in the sub-lexical route. In this view, it is reasonable to assume that stress and phonemes have similar time courses. Colombo and Zevin (2009) argued that stress neighborhood consistency might act as a cue to stress representation directly through phonetic activation. For an ending like -ato, which has a dominant stress neighborhood, the orthography may activate a phonetic realization including a tonic vowel (with long duration and high intensity for the /a/ vowel) that acts as a cue to the metrical structure of the stimulus. For an ending like -ano, with a non-dominant stress neighborhood, the phonetic realization of the first vowel, (an /a/ with relatively short duration and reduced intensity) would signal that the tonic vowel position has to be anticipated. This account assumes that the final part of a word (the rhyme) is phonetically coded and may emerge as a unit because of the strong connections between orthography and phonetics.

The proposal of Colombo and Zevin (2009) might account for stress neighborhood effects as follows. Let us consider an ending that occurs in words with stress on both the penultimate and the antepenultimate syllable, like -ica, (TRAgica, forMIca). A word like TRAgica is more likely to be

pronounced with initial stress, as most words ending in -ica bear initial stress. Because the final segments are phonologically the same in the two words, the advantage of TRAgica compared to forMIca would arise because the phonological representation of -ica is strongly associated with an abstract metrical representation in which the initial syllable is specified and this would transcode into its phonetic counterpart very quickly (Colombo & Zevin, 2009). The strong association between representations would allow faster processing of final strings with strong and consistent neighborhoods.

Syllables and stress.

A second issue pertaining to the phonology-to-phonetic interface not yet addressed by the reading literature is the relationship between syllables and stress. On the basis of studies reporting syllable frequency effects, Levelt and colleagues (1999) postulated a syllabary, which speakers access during phonetic encoding of the stimulus, and assumed that while new or rare syllables are assembled through an on-line procedure, frequent syllables are retrieved from a ready-made motor program repertoire, thus explaining the effect of syllable frequency. The question is the following: If we assume that syllables are represented in a ready-made format and that their access is sensitive to frequency, is it the frequency of the phonetic or of the phonological representation that matters? Levelt and colleagues' (1999) theory does not specify whether the abstract motor programs (corresponding to the syllables) stored in the syllabary are specified for stress. However, as noted above, the same syllable can be realized in two phonetically different ways depending on whether it is stressed (e.g., [ˈɒb] in OBject) or unstressed ([əb] in obJECT). Thus, a question to ask is whether syllables are phonetically represented as stressed, unstressed, or both.

The syllable frequency effect has been reported for reading (e.g., Carreiras, Mechelli, & Price, 2006; Carreiras & Perea, 2004). Note, however, that in order to explain this effect a syllabary might not

be necessary. This claim is based on a simulation carried out in our lab using the CDP++.Italian. In the CDP++ model, both orthographic input and phonological output are syllabically parsed, thus syllable representation is an essential feature of the model. If syllable frequency effects are obtained (even though no syllabary is included in the model), it follows that the notion of a syllabary is not crucial in explaining those effects. We were able to simulate the syllable frequency effect reported by Sulpizio and Job (2013: for behavioral data: $F1(1, 17)=22.19$; $p <.01$; for the simulation with CDP++.Italian: $F(1, 80)=4.953$, $p=.02$). We concluded that the syllable frequency effect might emerge from the frequent activation of connections between phonological and phonetic units.

Conclusions

The reviewed studies offer many hints about the nature of lexical stress and its role in reading aloud. Experimental evidence does not always perfectly converge, as shown by studies exploring the effect of the most frequent stress pattern, whether segmental and metrical representations are independently processed and whether priming is produced sublexically or lexically. In any case, quite a few robust effects have been found, enough to provide partial answers to the questions we initially raised, at least concerning how stress is lexically and sublexically assigned and how these processes develop. Specifically, in the absence (or limited presence) of stress rules, readers assign stress through two different mechanisms: a) by means of lexical activation, which allows the system to retrieve item-specific lexical-phonological knowledge from memory; b) through a sub-lexical procedure that exploits implicitly learned statistical properties and assigns stress using both the relative distribution of different stress patterns in the language (stress dominance) and the distribution of orthographic sequences that occur in many words and are strongly associated with a given stress pattern (i.e., stress neighborhood consistency).

In learning to read, the two mechanisms follow a different developmental trajectory. Lexical stress resulting from the acquisition of spoken language is available to children. However, the ability to assign stress sublexically develops through a trajectory that goes from more general reliance on the dominant stress in the language to more specific information drawn from stress neighborhood consistency, which becomes the preferred source of information for stress assignment in expert readers.

Metrical and segmental representations are, to some extent, independent as they may be selectively accessed by the reading system. However, the ability to access an abstract representation of stress, as exemplified by stress priming effects, needs time to develop, as shown by the absence of these effects in very young readers.

Furthermore, our review shows that many issues related to stress assignment in reading are still unresolved, such as for example the hypothesis of a strong orthography-to-phonetic relationship or the relationship between syllabic units and stress. Both experimental research and computational modeling have to further specify the processing details.

References

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

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: *Mental States: Language and Cognitive Structure*. Schalley, A. & Khlentzos, D. (Eds.), pp. 213-237. Amsterdam: John Benjamins Publishing.

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

Bates, E., Burani, C., D'Amico, S., & Barca, L. (2001). Word reading and picture naming in Italian. *Memory & Cognition, 29*, 986-999.

Bertinetto, P. M. (1980). The perception of stress by Italian speakers. *Journal of Phonetics*, *8*, 385-395.

Brown, P., Lupker, S. J., & Colombo, L. (1994). Interacting Sources of Information in Word Naming: A Study of Individual Differences. *Journal of Experimental Psychology: Human, Perception & Performance, 20*, 537-554.

Burani, C., & Arduino, L. S. (2004). Stress regularity or consistency? Reading aloud Italian polysyllables with different stress patterns. *Brain and Language, 90*, 318–325.

Burani, C., Paizi, D., & Sulpizio, S. (2014). Stress assignment in reading Italian: Friendship outweighs dominance. *Memory & Cognition*, *42*, 662-675.

Cappa, S. F., Nespor, M., Ielasi, W., & Miozzo, A. (1997). The representation of stress: evidence from an aphasic patient. *Cognition, 65,* 1-13.

Carreiras, M., Mechelli, A., & Price, C. J. (2006). Effect of word and syllable frequency on activation during lexical decision and reading aloud. *Human Brain Mapping*, *27*, 963-972.

Carreiras, M., & Perea, M. (2004). Naming pseudowords in Spanish: Effects of syllable frequency. *Brain and Language, 90,* 393-400.

Cholin, J., Dell, G. S., & Levelt, W. J. M. (2011). Planning and articulation in incremental word production: Syllable-frequency effects in English. *Journal of Experimental Psychology: Learning, Memory and Cognition, 37,* 109-122.

Chomsky, N., & Halle, M. (1968). *The sound pattern of English*. Harper and Row, New York.

Colombo, L. (1991). The role of lexical stress in word recognition and pronunciation. *Psychological Research, 53*, 71-79.

Colombo, L. (1992). Lexical stress effect and its interaction with frequency in word pronunciation. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 987-1003.

Colombo, L., Deguchi, C., & Boureux, M. (2014). Stress priming and statistical learning in Italian nonword reading: Evidence from children. *Reading and Writing*, *27*, 5, 923-943.

Colombo, L., & Tabossi, P. (1992). Strategies and stress assignment: Evidence from a shallow orthography. In R. Frost & L. Katz (Eds.), *Orthography, phonology,morphology, and meaning* (pp. 319–340). Amsterdam: Elsevier.

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

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*, 204 – 256.

Cutler, A. (2005). Lexical stress. In D. B. Pisoni, & R. E. Remez (Eds.). The handbook of speech perception (pp. 264-289). Oxford: Blackwell.

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Science, 15,* 3-10.

Hayes, B. (1995). *Metrical Stress Theory.* The University of Chicago Press, Chicago.

Holliman, A. J., Williams, G. J., Mundy, I. R., Wood, C., Hart, L., & Waldron, S. (2014). Beginning to disentangle the prosody-literacy relationship: a multi-component measure of prosodic sensitivity. *Reading and Writing, 27*, 255-266.

Holliman, A. J., Wood, C., & Sheehy, K. (2010). Does speech rhythm sensitivity predict children's reading ability 1 year later? *Journal of Educational Psychology, 102*, 356-366.

Howard, D., & Smith, K. (2002). The effects of lexical stress in aphasic word production. *Aphasiology*, *16*, 198-237.

Janssen, U., & Domhas, F. (2008). Going on with optimised feet: Evidence for the interaction between segmental and metrical structure in phonological encoding from a case of primary progressive aphasia. *Aphasiology, 22*, 1157-1175.

Kelly, M. (2004). Word onset patterns and lexical stress in English. *Journal of Memory and Language, 50*, 231-244.

Kelly, M., Morris, J., & Verrekia, L. (1998). Orthographic cues to lexical stress: Effects on naming and lexical decision. *Memory & Cognition, 26*, 822-832.

Jouravlev, O., & Lupker, S. L. (2014). Stress consistency and stress regularity effects in Russian. *Language and Cognitive Processes, 29,* 605-619.

Laganaro, M., Vacheresse, F., & Frauenfelder, U. H. (2002). Selective impairment of lexical stress assignment in an Italian-speaking aphasic patient. *Brain and Language, 81*, 601-609.

Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. Cambridge, MA: MIT Press.

Levelt, W. J. M., Roelofs, A., & Meyer, A. (1999). A theory of lexical access in speech production.

Behavioral and Brain Sciences, 22, 1-75.

Lukatela, G., & Turvey, M. T. (1990). Phonemic similarity effects and prelexical phonology. *Memory & Cognition*, *18*, 128-152.

Meyer, A. S., Roelofs, A., & Levelt, W. J. (2003). Word length effects in object naming: The role of a response criterion. *Journal of Memory and Language*,*48*, 131-147.

Miceli, G., & Caramazza, A. (1992). The assignment of word stress in oral reading: Evidence from a case of acquired dyslexia. *Cognitive Neuropsychology, 10,* 272-296.

Monaghan, P., Arciuli, J. & Ševa, N. (in press). Cross-linguistic evidence for probabilistic orthographic cues to lexical stress. In Thomson, J. & Jarmulowicz, L. (Eds.), *Linguistic rhythm and literacy.* Trends in Language Acquisition Research series (TiLAR). Amsterdam: John Benjamins Publishing..

Nespor, M., & Vogel, I. (1986). *Prosodic Phonology*. Dordrecht: Foris Publications.

Pagliuca, G., & Monaghan, P. (2010). Discovering large grain-sizes in a transparent orthography: Insights from a connectionist model of reading aloud for Italian. *European Journal of Cognitive Psychology, 22*, 813-835.

Paulesu, E., McCrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa, S. F., Cotelli, M., Cossu, G., Corte, F., Lorusso, M., Pesenti, S., Gallagher, A., Perani, D., Price, C., Frith, C. D., & Frith, U. (2000). A cultural effect on brain function. *Nature Neuroscience, 3,* 91-96.

Perry, C., Ziegler, J. C., & Zorzi, M. (2010). Beyond single syllables: Large-scale modeling of reading aloud with the Connectionist Dual Process (CDP++) model. *Cognitive Psychology, 61*, 106-151.

Perry, C., Ziegler, J. C., & Zorzi, M. (2014). CDP++. Italian: Modelling Sublexical and Supralexical Inconsistency in a Shallow Orthography. *PloS One*, *9*, e94291.

Protopapas, A., Gerakaki, S., & Alexandri, S. (2007). Sources of information for stress assignment in

reading Greek. *Applied Psycholinguistics, 28*, 695–720.

Rastle, K., & Coltheart, M. (2000). Lexical and Nonlexical Print-to-Sound Translation of Disyllabic Words and Nonwords. *Journal of Memory and Language, 42,* 342-364.

Rastle, K., Harrington, J., Coltheart, M., & Palethorpe, S. (2000). Reading aloud begins when the computation of phonology is complete. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1178-1191.

Roelofs, A. (2004). Seriality of phonological encoding in naming objects and reading their names. *Memory & Cognition, 32*, 212-222.

Roelofs, A. (in press). Modeling of phonological encoding in spoken word production: From Germanic languages to Mandarin Chinese and Japanese. *Japanese Psychological Research.*

Roelofs, A., & Meyer, A. (1998). Metrical structure in planning the production of spoken words. *Journal of Experimental Psychology: Learning, Memory and Cognition, 24*, 922-939.

Schiller, N. O., Fikkert, P., & Levelt, C. C. (2004). Stress priming in picture naming: An SOA study. *Brain & Language, 90*, 231-240.

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

Sternberg, S., Knoll, R. L., Monsell, S., & Wright, C. E. (1988). Motor programs and hierarchical organization in the control of rapid speech. *Phonetica, 45*, 175–197.

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

Sulpizio, S., Boureux, M., Burani, C., Deguchi, C., & Colombo, L. (2012a). Stress assignment in the development of reading aloud: Nonword priming effects on Italian children. In N. Miyake, D.

Peebles, & R. P. Cooper (Eds.), *Proceedings of the 34th Annual Conference of the Cognitive Science Society* (pp. 2369-2374). Austin, TX: Cognitive Science Society.

Sulpizio, S., & Burani, C. (in press). Reading segments is not reading words: Comment on Kawamoto et al. (2014). *Quarterly Journal of Experimental Psychology.*

Sulpizio, S., & Colombo, L. (2013). Lexical stress, frequency and stress neighborhood effects in the early stages of Italian reading development. *Quarterly Journal of Experimental Psychology, 66,* 2073-84.

Sulpizio, S., & Job, R. (2013). Syllable frequency and stress priming interact in reading Italian aloud. In M. Knauff, M. Pauen, N. Sebanz, & I. Wachsmuth (Eds.), *Proceedings of the 35th Annual Conference of the Cognitive Science Society* (pp. 1402-1407). Austin, TX: Cognitive Science Society.

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

Sulpizio, S., & McQueen, J. M. (2012). Italians use abstract knowledge about lexical stress during spoken-word recognition. *Journal of Memory and Language*, *66*, 177-193.

Thornton, A. M., Iacobini, C., & Burani, C. (1997). *BDVDB: Una base di dati sul vocabolario di base della lingua italiana.* [A database for the Italian basic dictionary]. Rome, Italy: Bulzoni..

Zhang, Q., & Zhu, X. (2011). The temporal and spatial features of segmental and suprasegmental encoding during implicit picture naming: An event-related potential study. *Neuropsychologia, 49,* 3813-3825.

Footnotes

1. Capital letters indicate the stressed syllable.

2. Some Italian words bear stress on the pre-antepenultimate syllable. These words usually include a long inflectional suffix (e.g., FABbricano, 'they produce') .

3. With regard to Russian, Jouravlev and Lupker (2014) did not define stress dominance and stress consistency in absolute terms, but relative to the grammatical class of words: Most Russian adjectives have initial stress, which becomes the dominant stress pattern for adjectives; a consistent stress orthography for an adjective is one that cues initial stress for a word with initial stress.