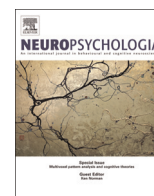Contents lists available at ScienceDirect

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# Phonological simplifications, apraxia of speech and the interaction between phonological and phonetic processing

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## ARTICLE INFO

## ABSTRACT

Research on aphasia has struggled to identify apraxia of speech (AoS) as an independent deficit affecting a processing level separate from phonological assembly and motor implementation. This is because AoS is characterized by both phonological and phonetic errors and, therefore, can be interpreted as a combination of deficits at the phonological and the motoric level rather than as an independent impairment. We apply novel psycholinguistic analyses to the perceptually phonological errors made by 24 Italian aphasic patients. We show that only patients with relative high rate ( > 10%) of phonetic errors make sound errors which simplify the phonology of the target. Moreover, simplifications are strongly associated with other variables indicative of articulatory difficulties – such as a predominance of errors on consonants rather than vowels – but not with other measures – such as rate of words reproduced correctly or rates of lexical errors. These results indicate that sound errors cannot arise at a single phonological level because they are different in different patients. Instead, different patterns: (1) provide evidence for separate impairments and the existence of a level of articulatory planning/programming intermediate between phonological selection and motor implementation; (2) validate AoS as an independent impairment at this level, characterized by phonetic errors and phonological simplifications; (3) support the claim that linguistic principles of complexity have an articulatory basis since they only apply in patients with associated articulatory difficulties.

## 1. Introduction

Apraxia of speech (AoS) is a diagnostic category often applied to describe speech production impairments following left-hemisphere lesions. It has a long history, with the term *verbal apraxia* being introduced by Liepmann at the beginning of the 20th century to indicate impairments affecting oral movements similar to those affecting limb movements, where there is no peripheral muscle weakness or spasticity, but still an inability to carry out meaningful actions or produce intended words. Consistent with this early view, the current, majority view of AoS is of a deficit of *articulatory planning*,[1] that is, of a deficit in the conversion of phonological into phonetic representations (e.g., see Darley et al., 1975; Duffy, 1995; McNeil et al., 2009; Van der Merwe, 1997; Laganaro, 2012). The patients know what they want to say – the phonological representation is intact – and there is no difficulty in

motor realization. Instead, what is affected is the process which converts a symbolic representation made up of discreet phonemes into a continuous plan which specifies motor targets and trajectories from one to the other. This impairment results in speech which is not systematically distorted but characterized by individual speech errors (phonological and phonetic) as well as by distorted prosody and visible/auditory efforts in controlling the articulators (groping).

In contrast with the view of a strict distinction between a phonological and a phonetic/planning stage, recent linguistic theories have argued that phonological representations should be phonetically grounded, with phonemic features expressed in terms of motor targets (e.g., Browman and Goldstein, 1992; Goldricket al., 2011; Ohala, 1990). This view could put into question a distinction between phonological impairments, involving phoneme selection, and AoS , involving articulatory planning. Still, one may argue that the motoric realization of phonemes depends on preceding and following segments. The stage where a contextual motor plan for a sequence of phonemes is constructed would correspond to articulatory planning and its impairment to AoS. Evidence for AoS as an independent impairment, however, is

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  [1] Please note that we will use the term planning as encompassing both what others have considered planning and programming (see Van der Merwe, 1997). Nothing hinges on this distinction for the present study.

lacking (e.g., see Ziegler et al., 2012 for a discussion of the independence of phonological and phonetic processing levels and the type of impairment in AoS). The purpose of this study is to provide this evidence by demonstrating that sound errors have special characteristics in AoS, which are compatible with an articulatory planning impairment. Our analyses will focus on what are perceptually phonological errors, but since we will demonstrate that these errors have an articulatory source we will use throughout the more impairment-neutral term 'sound production errors' (sound errors for short).

Clinically, AoS has been associated with a set of symptoms which can all be interpreted as arising from a disrupted articulatory planning process (e.g., Darley et al., 1975; McNeil et al., 2009; Laganaro, 2012; Wambaugh et al., 2006). Those cited consistently include: (a) phonetic errors – where phonemes are produced in a distorted way, sometimes associated with visible and audible groping; (b) sound errors, where phonemes different from the target are produced because of substitutions, deletions, insertions and transpositions; (c) a preponderance of errors on consonants rather than vowels; (d) slow/dysfluent speech with elongations of consonants and vowels and pauses between syllables and phonemes; (e) particular difficulties with initiating speech. All these symptoms can be explained by a generic difficulty with the motor planning of speech. An inaccurate articulatory planning process will produce phonetic errors where target oral configurations are not completely reached as well as phonological errors when a different target is planned or reached by mistake (although transposition of phonemes are perhaps more readily interpreted as difficulties with phonological selection than articulatory planning; see McNeil et al., 2009; Wambaugh et al., 2006). Since consonants are articulatorily more difficult than vowels they will be more susceptible to distortions and substitutions. A slower planning process will result in pauses between syllables and phonemes and/or in vowel and consonant elongations, to give the system enough time to organize the next bit of the articulatory program. Finally, a planning difficulty will produce repeated attempts to smooth production resulting in false starts. Unpacking what exactly a generic difficulty in motor planning entails, however, is more difficult. Different, not mutually exclusive, hypotheses are possible, but to formulate specific predictions is difficult and data-driven evidence is lacking.

One possibility is that AoS involves a loss of stored motor programs which specify which actions the bucco-facial apparatus has to perform to produce given units of speech. According to this view, motor plans for frequently co-occurring stretches of speech are stored and retrieved when needed. These plans can be of different sizes corresponding to phonemes, syllables, whole words or common phrases. Whiteside and Varley (1998) and Varley and Whiteside (2001) have explicitly hypothesized that (some) patients with AOS have lost the ability to access these stored plans and it is the need to assemble speech from smaller units which causes the dysfluency seen in the syndrome. In normal speakers, high-frequency routines should be accessed more easily than routines which are infrequent resulting in frequency effects. What to predict in the case of AoS, however, is less straightforward. According to Varley and Whiteside (2001), if access is lost, patients with AoS may show *no frequency effects* at all. Consistent with this possibility, Varley et al. (1999) reported no effects of word frequency on word durations in four patients with AoS. However, differences in duration did not reach significance even in control speakers and aphasic patients without AoS ($N=3$ in each group). More importantly, one could predict exactly the opposite of Varley and Whiteside. Brain damage may result in a loss of lower frequency routines and in a preservation of routines of higher frequency, with *enhanced frequency effects*, at least when syllables at the opposite ends of the distribution are considered (see Aichert

and Ziegler, 2004 for results consistent with this prediction).

Another possibility is that AOS does not involve a loss of stored representations but, instead, impaired computation of articulatory plans (a procedural/processing impairment). Even if frequently used motor plans can be retrieved in speech production, they need to be strung together and integrated into larger programs with co-articulation within and between syllables (Kelso and Tuller, 1981; Kent and McNeil, 1987; Ziegler, 2011). *Loss of fine motor skills* is perhaps an alternative terminology to indicate difficulties at this level, with a tendency to simplify clusters and other phonologically complex segments in AoS as supporting evidence (see Ziegler et al., 2012; Alajouanine et al., 1939). Different versions of this hypothesis, however, are possible and not all of them would necessarily entail phonological simplifications. Integrated motor plans may be disrupted because the necessary routines are *slow, error prone, or lack the necessary resources* to run smoothly, with these different sub-types of impairments resulting in dissociable error patterns (e.g., a *slow planner* may produce slower speech, an *imprecise planner* more phonetic errors and *lack of resources* syllabified speech and simplifications). Moreover, here, again these associations may not be straightforward because deficits may interact with one another and with the particular coping strategy adopted by the patient. For example, a reduction in resource capacity may result in false starts, inter-syllabic pauses and reduced co-articulation effects if the patient decides to reduce the size of the planning unit, but also in phonological simplifications if, instead, he decides to preserve fluency at the expense of accuracy. In addition, inaccurate/faulty routines may inevitably slow down the computational process and stretch resources, resulting in overlapping symptoms.

Studies trying to apply experimental paradigm to AoS are extremely limited. Rogers and Storkel (1999) tried to provide empirical evidence for a reduction in the capacity of an output buffer in patients with AoS using a paradigm where participants were asked to repeat pairs of words in rapid sequence (e.g., 10 times in a row). They reported that patients with AoS showed longer inter-word pauses with increased similarity of the words in the pair, at variance of normal controls or aphasic patients without AoS who showed no effect. They argued that this result was consistent with a reduced buffer. The apraxic patients would plan only one word at the time and clearing the buffer would be more time consuming in the case of overlapping information. Non-apraxic speakers could plan both words together, making unnecessary to clear the buffer and eliminating interference effects. Why interference effects should not be present when words are simultaneously in the buffer, however, is unclear and contrary to a large short-term-memory literature demonstrating phonological interference effects. This study, therefore, again outlines limitations in theoretical predictions and empirical evidence. Finally, a few studies have measured RTs in AoS. We have already mentioned the study by Varley et al. (1999). An early study by Towne and Crary (1988) showed that a patient with AoS had longer premotor preparatory time compared to non-apraxic speakers. Deger and Ziegler (2002) recorded reaction times for the production of nonsense words differing in length (2 vs. 3 syllables) or difficulty (same syllable repeated or different syllables). The apraxic patients had significantly longer word RTs (and onset RTs for second syllables) in the case of alternating syllables. Maas et al. (2008) asked patients with AoS to prepare to say a word and then say it as fast as possible when a go signal was presented. They found longer study time in the apraxic patients, but no differences in RTs. While these studies are consistent with difficulties of articulatory planning in patients with AoS, they fail to specify the nature of the difficulty. More worryingly, even if the effects described above (e.g., worse performance with syllables of lower frequency, worse performance with alternating syllables etc) were better documented, they could arise both at the phonological and at the articulatory level and we do not have clear criteria to identify *a priori* whether the patients are

suffering specifically from articulatory rather than phonological difficulties. We believe that to further our understanding of AoS we need to take a step back, and examine whether one could identify cluster of symptoms with higher degree of empirical association and theoretical coherence, starting from a main distinction between phonological and articulatory planning difficulties. This is the strategy embraced by the present study. The difficulty of the differential diagnosis of AoS is further outlined below.

The need to distinguish AoS from neighboring disorders such as dysathria and phonological aphasic impairments (e.g., Wernicke's and Conduction aphasia, from now on PhI) is well recognized (e.g., Ziegler et al., 2012). Distinguishing AoS from dysarthria, however, is the easier of the two. The etiology of dysarthria is often different, involving subcortical damage and bilateral impairments, and the quality of speech is generally systematically affected, with few or no clear sound errors and few or no attempts on the part of the patient to self-correct (but instead with systematic distortions such as a strangled quality or hypernasality or reduced loudness etc.). These different characteristics make the speech of dysarthric patients distinct. The differential diagnosis of AoS and PhI is more complicated and, in fact, is one of the thorniest issues in aphasiology (e.g., Ballard et al., 2000; Code et al., 2011; Duffy, 2005; McNeil et al., 2009; Laganaro, 2012). The main source of difficulty is that errors that are perceptually phonological characterize both AoS and PhI, and both patterns can involve mainly consonants. The other two potentially distinguishing characteristics, i.e., phonetic errors and slow speech, are also problematic.

Theoretically, it is not clear why a slow/dysfluent speech should characterize apraxic, but not phonological impairments. First of all, speech dysfluency is very common in aphasia and can be motivated by a variety of causes which are not easy to disentangle just by listening to the speech. Difficulties with sentence construction and lexical retrieval will disrupt the flow of speech as much as phonological and apraxic difficulties. One could focus on word durations in a task like single word repetition, which does not involve sentence construction and reduces the need for lexical access. However, even here, patients may take longer to produce single words either because they have difficulties compiling an articulatory plan or because they have difficulties selecting the right phonemes. Both difficulties could result in elongation of segments and/or discontinuities between them. Articulatory difficulties could disrupt speed more often than phonological difficulties, but empirical findings are, at best, inconclusive. Several studies have failed to find significantly slower speech in patients with AoS than PhI (Kent and McNeil, 1987; McNeil et al., 1990). Instead, a large overlap between groups has been reported, with patients from both groups willing to trade off speed for phonemic accuracy (McNeil et al., 2009; Seddoh et al., 1996; groups were subdivided on the basis of perceptual judgments by S&L therapists, as is standard in the field, and presence of trial and error groping in the apraxic group only).

Phonetic errors are a more direct sign of articulatory difficulties. Assessing their frequency, however, is not always easy. Given the categorical bias in human perception, what is perceived as a phonological error may, in fact, be a phonetic error where the motor realization is different enough from the target to be perceived as a different phoneme. Therefore, without labor-intensive spectrographic analyses to identify non-canonical profiles, the frequency of phonetic errors and, consequently, apraxic impairment, may be under-estimated. From the opposite point of view, phonetic errors may not be an invariable sign of articulatory difficulties. A number of recent studies have shown that even speech errors made by normal speakers and which arise from perseveration or anticipation of phonemes often have acoustic properties intermediate between those canonical for the target and the error (Frisch and Wright, 2002; McMillan and Corley, 2010; Pouplier, 2005). These errors may arise because multiple, simultaneously active phonemes influence the selection of an articulatory plan that ends up with intermediate parameters. According to this proposal, therefore, errors which are perceptually phonetic can also result from selection difficulties at the phonological level, not just articulatory difficulties.

A lack of theoretical and empirical clarity has led to doubt the very existence of AoS. For example, one of the most influential schools of aphasiology, the Boston school, completely dispensed with AoS (see Goodglass and Kaplan, 1985). In typical studies, patients are categorized by clinicians and, then, compared on a series of variables. However, consistency of diagnosis on the basis of clinical impression is far from good. While one recent study reported high consistency (Mumby et al., 2007), another reported staggering levels of inconsistency, at least when criteria were not specifically calibrated (Haley et al., 2012). Secondly, consistency, in itself, does not imply correct diagnosis. As discussed, perceptional analyses of speech may under-detect phonetic errors and underestimate apraxic impairments. Finally, even relying on a combination of signs cannot guarantee correct classification of AoS since similar combinations are found in PhI. This unsatisfactory state of affairs justifies the possibility that AoS is not an independent impairment, but a *chimera* arising from the juxtaposition of separate impairments at the phonological and at the phonetic/dysartric level.

To further our understanding of post-lexical access disorders, we need to find out which speech characteristics cluster together and whether these clusters are theoretically well motivated and empirically able to distinguish different impairments. To do so, we may start by classifying patients on the basis of one quantifiable and theoretically meaningful measure and, then, assess differences on other measures (see also Haley et al., 2012 for a powerful argument for this position). Additionally, we may want to assess correlations between different measures and/or run cluster analyses without any a-priori classification of the patients. Finally, we need to extend analyses to include new measures which can support and extend existing clinical criteria. We do all of this in the present study.

Given the arguments against speech fluency, we will consider rate of perceived phonetic errors as the best current, quantifiable criteria to identify apraxic difficulties. The obvious area to examine to find an additional distinguishing characteristic is sound errors, since they are so pervasive across patients. Some studies have looked the consistency of errors in patients with AoS vs. PhI, but results have not been encouraging. Consistency varied across patients (Staiger et al., 2012), but not between groups, at least when these were identified on the basis of speech fluency (Haley et al., 2012). In the current study we take a different approach and look at whether errors do or do not simplify target syllables and phonemes. In some of our previous studies, we have argued that sound errors may have two distinct sources. They may arise at the level of phoneme selection because the phonological representation is degraded and some information is missing or difficult to activate. In this case, selection between alternatives will be governed by phonemic similarity, but not by complexity. Alternatively, sound errors may be motivated by difficulties in articulatory planning as a means to simplify representations that are too difficult to be realized successfully (see Romani et al., 2002; Romani and Galluzzi, 2005; Romani et al., 2011a; see also Code, 1998; Code and Ball, 1982). In this case, errors will be similar in type and purpose to those made by children acquiring language and reflect a reduction in the level of phonological complexity allowed by the grammar of the speaker at a given moment in time. Thus, errors will systematically produce phonemes and syllables which are simpler than the target.

If we are correct in postulating this double nature of sound errors, the presence vs. absence of a simplification pattern can be a powerful tool to identify AoS and to show that there is a

processing level intermediate between phonology and motor realization. Before we move on to outline the design of our study, we will briefly review current evidence regarding simplification patterns in the phonological errors of aphasic patients.

## 2. Phonological paraphasias in different aphasic syndromes

The influential studies by Blumstein (1973, 1978) reported no differences between patient groups in the type of sound errors they produced (see also Holloman and Drummond, 1991). Early on, however, other studies reported differences between groups, with apraxic patients showing a stronger concentration of errors on consonants (Burns and Canter, 1977; Monoi et al., 1983) as well as more substitutions closer to the target and fewer sequencing errors (Canter et al., 1985). Syllabic simplifications have also been shown to be more prevalent in patients with AoS than in patients with PhI (see Keller, 1984; Goldrick and Rapp, 2007; Nespoulous et al., 1984; Romani and Galluzzi, 2005; Romani et al., 2011a,b; see also Edmonds and Marquardt, 2004; Staiger and Ziegler, 2008 for evidence of syllable complexity effects in patients with AoS, but without a contrasting group). Evidence for different patterns in the case of individual phoneme simplifications, however, is less complete.

A number of studies have also provided evidence that patients with AoS reduce the markedness (complexity) of individual phonemes (Cera and Ortiz, 2010; Klich et al., 1979; Odell et al., 1990; Marquardt et al., 1979; Wolk, 1986; but see Dogil and Mayer, 1998[2]), but what happens in patients with PhI is less clear and there is a lack of comparative evidence. Blumstein (1973), again, stressed similarity across patient groups (see also Kohn et al., 1998), but other studies have reported differences. Nespoulous et al. (1987) contrasted phonemic substitutions in four patients with AoS/Brocas aphasia and four with conduction aphasia (CA) in reading and repetition. By analyzing a large corpus of errors in repetition and in reading, they found strong markedness effects in patients with AoS/BA with simplifications for voicing (devoicing tendency), manner (stopping tendency) and place of articulation (fronting tendency; see later for explanations), but no markedness effects in patients with CA. Unfortunately, this study focused more on differences between tasks (not replicated by later studies) than on differences in simplifications, reducing the impact of their results in the literature. Goldrick and Rapp (2007) reported more place simplifications in the sound errors of a patient with a post-lexical phonological disorder than in a patient with a more central lexical impairment, but their data were limited: only two patients, very few errors and only a contrast between the coronal consonants /d,t/ and the velar consonants /k,G/. The strongest evidence comes from our previous papers where groups of patients were subdivided on the basis of rate of phonetic errors (Romani et al., 2002; Romani and Galluzzi, 2005; Romani et al., 2011a). However, these studies mainly focused on syllabic simplifications in terms of deletions and insertion errors. Analyses involving phoneme substitutions were reported only as part of

general analyses and simplifications were assessed in terms of the sonority profile of the syllable rather than in terms of phoneme markedness per se.

Since substitutions are the most common type of sound errors made by aphasic patients, it is clearly important to demonstrate that they show distinct patterns. Phonemic simplifications, where one or more distinctive features are replaced with simpler counterparts should be more common in patients with higher rates of phonetic errors.

## 3. Aims and plan of study

Our study has two main aims. The first aim is to strengthen the evidence that a tendency to simplify can be taken as an important characteristic that differentiates speech production impairments and, potentially, as a hallmark of AoS. To do this, we will use a preliminary subdivision of patients on the basis of rate of phonetic errors using a cut-off of $> 10\%$ for potentially apraxic patients and $< 5\%$ for the phonological patients (see Romani and Galluzzi, 2005; Romani et al., 2011a,b). We will then compare the rate of simplification of syllables and phonemes in the two groups, as well as different types of phonemic simplifications. Our expectation is that, across simplification types, the tendency to simplify will be much stronger in the apraxic than in the phonological patients. Moreover, we expect only phonological patients to make higher error rates on vowels since these are articulatory easier than consonants (see Fig. 1 for a depiction of criteria linked to levels in a processing model).

The second aim is to provide evidence that different production measures which are thought to be fundamental to a diagnosis of AoS are associated. We will, therefore, assess correlations between: (a) phonetic errors (reflecting perceptually distorted phonemes and/or groping accompanied by artculatory effort), (b) simplification errors, (c) word durations (reflecting segmental elongations as well as inter-segmental and inter-syllabic pauses), and (d) the relative rate of consonants vs. vowel errors. The results of correlation analyses are important to complement what is found using discreet groups of patients. Brain lesions do not respect cognitive boundaries and often patients suffer from more than one cognitive impairment. Overlap will be significant, especially for impairments affecting neighboring processing components – such as phonological and apraxic impairments. This does not mean that identifying the most common impairment is not possible or useful in the majority of patients (to monitor progress and guide rehabilitation), but it is important not to limit analyses to discreet patient groups. If syllabic simplifications are related to apraxic difficulties, they should correlate with other measures of articulatory difficulties, such as rate of phonetic errors and prevalence of consonant errors, across the **whole** group and independently of severity of impairment. Instead, they should not correlate, or correlate negatively, with a measure of lexical impairment such as rate of lexical errors. The contrasting hypothesis – that all sound errors, including simplifications, arise from the same phonological impairment – has no reason to predict that simplifications will show these selective associations. Instead, correlation patterns may be a function of differences in severity (e.g. see the 'continuity thesis', Schwartz et al., 2006). What to expect in the case of word durations is more unclear. Word durations and phonetic errors may be related because they reflect the same impairment, but also, more generally, because they reflect severity of impairment. Word durations, instead, may not be related to rate of simplification which reflects a qualitative pattern, independent of severity (it is a ratio comparing type of errors, no matter how many errors there are). If both difficulties of selection and difficulties of articulatory planning can slow down of speech

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[2] Dogil and Mayer (1998) reported paradoxical markedness effects in a patient speaking Xhosa, a Bantu language. The patient – MQ – was diagnosed with AoS on the basis of phonological substitutions and articulatory groping (deletions and insertions of phonemes and phonetic distortions were reported to be few). Paradoxically, MQ made fewer errors on more difficult sounds such as clicks than on easier sounds such as coronal obstruents. However, the direction of the errors was generally not reported. The authors only observe that implosives and ejectives were replaced by oral stops, which, in fact, is consistent with a simplification pattern. Why clicks and affricates were preserved in this patient is not clear. The authors' explanation that MQ's pattern arises from *having lost phoneme under-specification* is not plausible. Over-specification of features should result in over-articulation of phonemes, not in phonological substitutions. Moreover, it is difficult to think that brain damage would directly result in richer, more specified representations without some other processing to be missing.
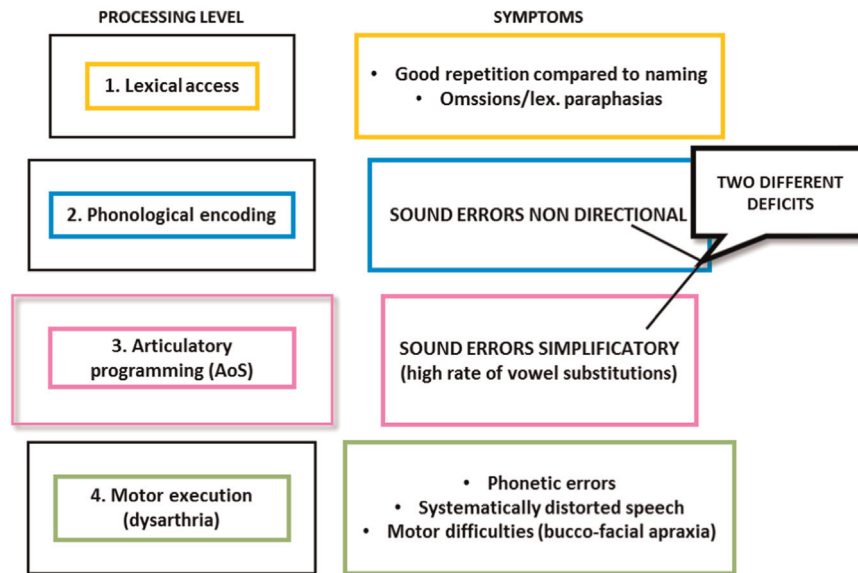
**Fig. 1.** Schematic word production model indicating possible diagnostic criteria for different impairments.

production, as we argued, the association should be weak.

Finally, we will carry out cluster analyses to subdivide patients, bottom up, without any *a priori classification*. We will assess the strength of different variables in providing this subdivision as well as how groups fare on different 'evaluative' variables. We expect that the apraxic group will show more signs of bucco-facial apraxia since their impairment is closer to motor implementation, while the phonological group will show higher rates of lexical errors since these are errors which arise higher up in lexical access.

## 4. Background

Our study involves 24 Italian aphasic patients referred to us by two rehabilitation clinics in Rome: Fondazione Santa Lucia and Clinica Villa Fulvia. Most of the patients came from Rome and the surrounding areas; they spoke good standard Italian, but some of their pronunciations (particularly consonant degemination) may have been affected by Roman dialect. A smaller group of these patients was involved in the study by Romani and Galluzzi (2005) which demonstrated that phonological complexity predicted performance in patients with high rates of phonetic errors, but not in patients with low rates. The same cohort of patients participated in the study by Romani et al. (2011a) which showed that, although patients that make different rates of phonetic errors differ in their tendency to simplify syllable structure, all patients remain as faithful as possible to the original syllabic structure of the word. This demonstrated that syllable structure is an important characteristic of words which is stored together with other phonological features.

### 4.1. Reliability

All spoken responses were tape-recorded to allow rechecking. They were transcribed and categorized by the first author, but spot-rechecked by the last authors with disagreements settled through discussion. A sample of the patient responses was also checked for scoring consistency by a neuropsychologist extraneous to the study ($N=1550$ responses from five patients, 3 apraxic and 2 phonological). Responses were classified as: 1. correct, 2. sound errors, 3. phonetic errors. Overall consistency was high = 90%; it was lower if only phonetic errors were considered = 76%. This was

expected given a general difficulty in detecting phonetic errors.

## 5. General characteristics of patients

Biographical and clinical details are reported in Table 1 together with rates of phonetic errors and scores on a test of bucco-facial apraxia.

### 5.1. Phonetic errors and experimental classification

Rates of phonetic errors were established by having two of the authors carefully listen to the patients' recorded single word repetition. These analyses were carried on repetition since errors in reading and naming may reflect difficulties not only with speech production but also with orthographic processing and lexical access.

Phonetic errors included the following types:

1. Slurred phonemes: A stretch of speech or a whole word produced in a slurred fashion; systematically slurred speech is associated with dysarthria (e.g., Duffy et al., 2007), but stretches of slurred speech also occur in patients with AoS;
2. Distorted phonemes: Included in this category are lenitions – well-formed phonemes produced with less articulatory force (e.g., see Ash et al., 2010) - and phonemes produced with a perceptible deviation from the target in place, manner or timing (see Kent and Rosenbek, 1983; Odell et al., 1990; McNeil et al., 1990);
3. An audible or, more rarely, visual effort in producing the word, generally at word beginning (for initiation difficulties see Kent and Rosenbek, 1983; Strand and McNeil, 1996; for effortful trial and error and groping, see McNeil et al., 1990, 2009; Odell et al., 1990).
4. Patients making over 10% of phonetic errors in single word repetition were classified as *Apraxic*, those making less than 5% errors as *Phonological* and those with intermediate scores as *Mixed*. All patients suffered from a left hemisphere stroke except GM who suffered a right CVA and DS who suffered a close head injury. All patients were clinically stable and none demonstrated marked changes in performance during the testing period.

**Table 1**

Anagraphical and clinical characteristics of patients. Number of phonetic errors are assessed in single word repetition; Slurred=segments produced in a slurred way; Distorted=individual phonemes produced in an imprecise way; Art. effort (articulatory effort)=audible or visible efforts in producing speech. n.t.=patient not tested because the task is too difficult; - =task not administered.

| | Age | Sex | Months post onset | Ethio logy | Site of lesion | Phonotic errors | | | | | | Bucco-facial apraxia |
| | | | | | | Target | Slurred | Distorted | Art. effort | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Apraxic | | | | | | N | N | N | N | N | % | |
| AM | 52 | M | 144 | cva | Left temporal | 773 | 52 | 130 | 14 | 196 | **25.4** | 14 |
| AP | 60 | M | 4 | cva | Left basal nucleus | 773 | 34 | 62 | 0 | 96 | **12.4** | 18 |
| AV | 64 | F | 14 | cva | Left fronto-parietal | 574 | 108 | 6 | 8 | 122 | **21.3** | 16 |
| DC | 55 | M | 6 | cva | Left fronto temporo- parietal | 735 | 25 | 73 | 3 | 101 | **13.7** | 17 |
| DG | 30 | F | 5 | cva | Left temporo-basal, insula, internal capsule | 773 | 37 | 54 | 12 | 103 | **13.3** | 20 |
| EM | 59 | M | 16 | cva | Left temporo-parietal | 390 | 11 | 35 | 18 | 64 | **16.4** | 16 |
| GC | 55 | M | 24 | cva | Left basal, internal capsule | 773 | 26 | 43 | 40 | 109 | **14.1** | 12 |
| MI | 54 | M | 24 | cva | Left temporo parietal | 684 | 15 | 87 | 62 | 164 | **24.0** | 12 |
| OB | 73 | F | 4 | cva | Left fronto-temporo-parietal | 757 | 25 | 93 | 6 | 124 | **16.4** | – |
| PV | 50 | F | 264 | cva | Left fronto-temporo-parietal | 750 | 24 | 84 | 21 | 129 | **17.2** | 12 |
| SR | 68 | M | 6 | cva | Left fronto-temporo-parietal | 773 | 41 | 28 | 10 | 79 | **10.2** | 16 |
| Mixed | | | | | | | | | | | | |
| AG | 70 | M | 3 | cva | Left periventricular | 773 | 7 | 48 | 0 | 55 | **7.1** | 20 |
| CA | 73 | F | 3 | cva | Left parietal | 773 | 15 | 33 | 1 | 49 | **6.3** | 20 |
| MS | 48 | M | 9 | cva | Left fronto-temporal | 576 | 5 | 18 | 8 | 31 | **5.4** | – |
| PM | 64 | M | 3 | cva | Left and right temporo-parietal | 773 | 1 | 62 | 0 | 63 | **8.2** | n.t. |
| Phonological | | | | | | | | | | | | |
| AC | 71 | F | 5 | cva | Left fronto-temporal | 627 | 1 | 6 | 0 | 7 | **1.1** | 20 |
| DS | 23 | M | 4 | closed head injury | Left fronto-temporo-parietal | 718 | 0 | 24 | 0 | 24 | **3.3** | 20 |
| GM | 65 | M | 4 | cva | Right parietal | 773 | 9 | 5 | 0 | 14 | **1.8** | 20 |
| LB | 72 | M | 3 | cva | Left fronto-temporo-parietal | 773 | 15 | 17 | 3 | 35 | **4.5** | 20 |
| MC | 71 | M | 6 | cva | Left parietal, post. insula | 534 | 6 | 14 | 1 | 21 | **3.9** | 20 |
| MP | 66 | M | 4 | cva | Left temporo-parietal | 773 | 0 | 4 | 0 | 4 | **0.5** | 19 |
| RM | 70 | M | 15 | cva | Left parietal | 754 | 8 | 4 | 6 | 18 | **2.4** | 20 |
| TC | 32 | F | 7 | cva | Left fronto-temporal | 773 | 3 | 1 | 7 | 11 | **1.4** | 20 |
| VS | 60 | M | 2 | cva | Left parietal-occipital | 773 | 5 | 33 | 0 | 38 | **4.9** | 19 |
| $G^2$ | | | | | | | | | | | | 2.91 |
| $p$ | | | | | | | | | | | | **.09** |

## 5.2. Clinical classification

Apart from possible associated AoS, all of our patients have a mild to severe repetition impairment and good comprehension which fits a classification of conduction rather than anomic aphasia. A label of Broca's/global aphasia, however, would be more appropriate for some patients in the apraxic sub-group given the agrammatic and effortful nature of their speech. We believe that not much should be taken from the clinical classification of the patients. A sample of the patients' speech is reported in Appendix A.

## 5.3. Lesions

Lesion analysis was based on neuroradiological clinical examination made by the hospitals during acute and sub-acute phases of stroke, before patients were admitted to the rehabilitation clinics. Therefore, due to the high variability in the reported data (some scans were RM scans, some were CT; some data were on digital supports, some were radiological images of variable quality) any quantitative analysis was impossible. Patients in the apraxic group appear to have frontal and subcortical lesions more often, but our information is too limited to carry out statistical analyses. Voxel-based symptom-lesion mapping should be used by future studies to distinguish lesion sites in patients with different types of sound errors (e.g., see Schwartz et al., 2012, for a distinction between phonological and semantic errors).

## 5.4. Bucco-facial apraxia

Patients were administered the Spinnler and Tognoni (1987) test of bucco-facial apraxia, which includes 20 commands of the type 'puff out your cheeks', 'move your tongue back and forth to the side of your mouth' etc. There has been a lot of controversy regarding whether AoS is a generalized motor impairment involving oro-facial movements or, whether, instead, it selectively affects speech movements. Comprehensive reviews on this topic have reached opposite conclusions (Ziegler, 2003; Ballard et al., 2000). A number of studies have reported dissociations between performance on tasks of bucco-facial apraxia and AoS (Ziegler, 2003; Bizzozero et al., 2000), but it has been argued that bucco-facial tasks are generally easier and that patients with AoS are indeed impaired with more taxing non-speech tasks (Ballard et al., 2000). Our results exemplify the paradox the field is struggling with. The apraxic patients performed significantly worse than the phonological patients. This supports the hypothesis that similar mechanisms underlie speech movements and other oro-facial movements. On the other hand, DG, who performed flawlessly in our apraxia battery, showed a relatively high proportion of phonetic errors, slow speech and a significant tendency to simplify (see later). This double dissociation indicates some independence in the mechanisms used to plan/program speech and more general oral movements. Minimally, however, our results also demonstrate that the brain areas involved in controlling speech movements and other oro-facial movements are represented in close proximity or are closely interlinked so that they are likely to be damaged

together.

### 5.5. Additional neuropsychological assessment

All patients were administered a comprehensive neuropsychological battery assessing: 1. *phonological discrimination* with same-different minimal pairs of syllables (ta-ta vs. ta-da) and minimal pairs of words and non-words (e.g., words: castello/pastello; non-words: caruci/camuci); 2. *lexical input* with a lexical decision task (non-words were derived from the same words by changing 3 letters); 3. *syntactic processing* with a sentence picture matching task (including active and passive sentences with semantic, morphological and lexical disctractors) and 4. *semantic processing* with a word-picture matching task (including semantic and phonological distractors). Results are reported in Appendix B.

All patients had little or no difficulty in tasks tapping phonological input and lexical semantic processing. Exceptions were CA, with some problems in the same-different tasks, and MC, with some difficulties in lexical decision and word–picture matching. Difficulties with sentence––picture matching were more widespread, but this is consistent with a diagnosis of aphasia and is not directly related to phonological difficulties.

## 6. Experimental investigation

### 6.1. Materials

To assess word production difficulties, patients were administered three tasks involving reading and repetition of single words and picture naming. Reading and repetition included 776 words from five lists contrasting effects of word frequency, phoneme length, concreteness, phonological complexity and grammatical class. For repetition, the word was spoken aloud by the experimenter and the patient was asked to repeat it right away. The experimenter repeated the word again if the patient asked for it. For reading, words were presented on cards written in a large font. Different patients did either a longer ($N=412$) or a shorter version ($N=238$) of the naming test; the shorter test included a list assessing effects of length and frequency and a second one with pictures corresponding to a subset of the words administered in repetition and reading. All pictures were black and white drawings presented individually on a sheet of paper (for more details on testing materials see Romani et al., 2011a,b). The first full response was scored.

### 6.2. Statistical analyses

Some of our statistical analyses will involve comparing error rates in apraxic and in phonological patients. Since these are binary measures, we assessed differences using binary logistic regressions with 'patient group' as a fixed factor and individual 'patient' as a random factor nested within group (statistics reported as likelihood ratio $G^2$).

### 6.3. General error characteristics across tasks

Overall performance in repetition, reading and naming is shown in Table 2, which also shows relative proportions of lexical and non-lexical errors and types of individual non-lexical errors in repetition. Consistent with our selection criteria, all patients had difficulties across tasks. Performance was generally better in repetition than naming. Differences were significant only for the apraxic patients (apraxic: $t=4.08$, $p=.003$; mixed: $t=1.26$, $p=.29$; phonological: $t=1.89$, $p=.095$), but size of difference was similar across the apraxic and the phonological group. Across groups, patients made a majority of non-lexical errors and in all patients, the majority of the non-lexical errors affected the production of

**Table 2**
Overall performance across tasks. % correct is $N$ of words correct out of target words. Lexical and non-lexical errors are out of total number of words incorrect excluding omissions and circumlocutions which occurred only in naming. Individual non-lexical errors involve up to three non-consecutive phonemes, including geminate errors. Order errors include exchanges, switches and shifts were a phoneme is moved from its original position to a new position, but not anticipatory/perseveratory substitutions and insertions.

| | Apraxic | | | Mixed | | | Phonological | | | $G^2$ | $p$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $N$ | Mean % | SD | $N$ | Mean % | SD | $N$ | Mean % | SD | Aprax. vs. Phonol. | |
| **Correct** | | | | | | | | | | | |
| Repetition | 4065 | **47.8** | 22.6 | 1780 | **59.3** | 21.2 | 4611 | **66.3** | 24.7 | 2.00 | .16 |
| Reading | 3731 | **48.7** | 17.6 | 2110 | **68.2** | 17.3 | 5030 | **73.8** | 19.9 | 6.36 | **.01** |
| Naming | 1200 | **35.3** | 17.9 | 426 | **44.8** | 16.0 | 1817 | **57.2** | 17.0 | 4.22 | **.04** |
| Difference **rep**-nam | 2865 | **12.5** | | 1354 | **14.5** | 11.5 | 2794 | **9.2** | | 1.02 | .32 |
| | | | | | | | | | | | |
| **Lexical errors** | | | | | | | | | | | |
| Repetition | 398 | **9.0** | 4.6 | 232 | **19.3** | 4.2 | 380 | **16.3** | 13.5 | 4.23 | **.04** |
| Reading | 709 | **18.4** | 10.5 | 230 | **23.4** | 13.6 | 340 | **19.0** | 8.1 | 0.54 | .46 |
| Naming | 458 | **29.5** | 13.9 | 170 | **33.5** | 13.8 | 476 | **42.5** | 19.1 | 2.27 | .13 |
| Difference nam-**rep** | 60 | **20.5** | 12.2 | 62 | **14.3** | 14.9 | 96 | **26.2** | 18.5 | T=2.0 | .17 |
| | | | | | | | | | | | |
| **Individual non-lexical Errors** | | | | | | | | | | | |
| Repetition | 4090 | **77.1** | 13.6 | 868 | **71.4** | 9.7 | 1799 | **73.2** | 8.8 | 0.64 | .53 |
| Reading | 3152 | **80.2** | 7.9 | 583 | **66.3** | 10.1 | 1275 | **75.7** | 10.3 | 1.09 | .29 |
| Naming | 944 | **73.5** | 15.3 | 250 | **62.5** | 7.6 | 544 | **74.1** | 12.2 | 0.62 | .54 |
| | | | | | | | | | | | |
| **Types of individual errors** | | | | | | | | | | | |
| (in repetition) | | | | | | | | | | | |
| Substitutions | 2636 | **64.4** | 10.4 | 611 | **70.4** | 3.7 | 1238 | **68.8** | 4.1 | 1.48 | .22 |
| Deletions | 892 | **21.8** | 9.4 | 115 | **13.2** | 3.4 | 231 | **12.8** | 5.0 | 6.09 | **.01** |
| Insertions | 358 | **8.8** | 4.0 | 106 | **12.2** | 3.4 | 197 | **11.0** | 3.4 | 1.78 | .18 |
| Order errors | 204 | **5.0** | 3.0 | 36 | **4.1** | 1.8 | 133 | **7.4** | 3.5 | 0.15 | .70 |

discreet phonological segments resulting in a majority of individual sound errors. Across patients, substitutions were the most common errors (the only exception was AV who made more deletions) and order errors were rare. Deletions and insertions had intermediate frequency. However, the apraxic patients made significantly more deletions than insertions ($t=3.94$, $p=.003$) while the mixed and the phonological group showed more balanced rates (mixed: $t=0.97$, $p=.39$; phonological: $t=1.724$, $p=.12$). Rates of lexical errors were marginally higher in phonological patients in repetition and naming, consistent with a more central impairment.

We also analyzed substitution errors in terms of feature overlap with the target. Our expectation was that errors arising at a more central, symbolic level of phonological representation would show less overlap than errors arising more peripherally, in planning or implementing motor commands. Analyses have been carried out using a feature matrix adapted from Chomsky and Halle (1968). Results are shown in Fig. 2. It is clear that the apraxic and the phonological groups show different profiles with the mixed patients in the middle. The apraxic patients make more errors involving single features (for repetition, reading and naming $\chi^2=43.3$; 154.5; 33.6; all $p<.001$), while the phonological patients made more errors involving 2–3 features and 4–6 features (across tasks: $\chi^2=7.3$-68.8; $p=.007$- $<.001$).

## 6.4. Discussion

General error characteristics indicate that the main deficits arise at a level following lexical selection. Repetition, reading and naming all involve a stage where the phonemes for the words need to be retrieved and then converted into articulation. Difficulties in lexical access, instead, should result in more severe impairments in naming than repetition (see Goldrick and Rapp, 2007). Our patients showed worse performance in naming, but discrepancies were not marked and they were similar across groups, suggesting similar contribution of difficulties in lexical access. The fact that the majority of errors affected single phonemes is also consistent with an impairment after lexical access. Marginally higher rates of lexical errors in the phonological patients, together with higher signs of bucco-facial apraxia in the apraxic patients, however, are early signs of differences between the groups. Lexical deficits should be more associated with

phonological impairments and motor deficits with apraxic impairments. Similarly, different degrees of feature overlap in the errors of phonological and apraxic patients are early signs that these errors have different sources.

## 6.5. Types and rates of phonological simplifications

Some structures are acquired earlier by children and have a wider distribution within and across languages. These differences can be explained by assuming that some structures (unmarked) are easier to produce than others (marked) and for this reason are acquired earlier and are used more widely (see Bermúdez-Otero and Börjars, 2006; Kingston, 2007; de Lacy, 2006; Ohala, 1997 for a discussion of how markedness principles may be grounded in articulation). Here, we will use principles of syllabic and segmental markedness to assess the direction of sound errors. Errors which will reduce markedness will be considered simplifications, errors in the opposite direction will be considered complications and errors which do not modify markedness will be considered neutral. Note that deletions and insertions errors mainly affect the complexity of syllable structure, while substitution errors mainly affect phonemic complexity or sonority. Transposition errors rarely affect complexity.

We assessed errors along four dimensions of phonological complexity which are relatively uncontroversial, at least when broad contrasts are considered (for distributional results see Greenberg, 1966/2005; Maddieson, 1984; for corpora of developmental data see: Stoel-Gammon, 1985; Smit et al., 1990; Zanobini et al., 2012; Zmarich and Bonifacio; 2005):

### 6.5.1. Complexity of syllables

Syllables made by a consonant + a vowel (CV) are the simplest type and all progressive modifications of this basic template are complications (e.g., see Kaye and Lowenstamm, 1981). Thus, we considered deletion and insertion errors which eliminate complex onsets (e.g., CCV > CV; CCV > CV.CV), codas (e.g., CVC > CV; CVC > CV.CV) and hiatuses (e.g., V.V > V; V.CV) to be simplifications.

### 6.5.2. Complexity of the transition across syllables

Changing the point of articulation is harder than maintaining the same point of articulation; thus, producing a long (geminate)
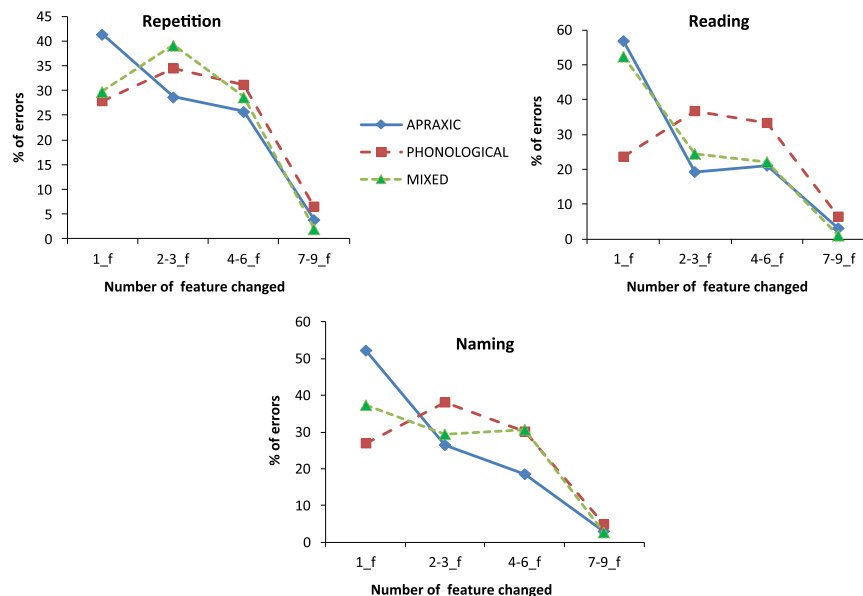


Fig. 2. Rates of substitutions errors by number of feature changed.

consonant is easier than producing a consonant cluster (as demonstrated by the errors made by children across languages, see Bernhardt and Stemberger, 1998). Italian has a high proportion of geminate consonants (consonants spanning two timing units across a hetero-syllabic boundary; e.g., /pal.la/ [ball] vs. /pa.la/ [spade]). We considered to be simplifications errors where a cluster was assimilated to a geminate ($VC_1.C_2V > VC_2.C_2V$); errors in the opposite direction were classified as complications; errors where a geminate was substituted with another geminate or a cluster with another cluster were classified as neutral.

### 6.5.3. Complexity of phonemes in terms of sonority

According to the sonority dispersion principle (SDP, Clements, 1990), the best sonority profile for a syllable is peaked, with a sharp rise of sonority from the margin of the syllable to the vowel. Instead, sonority should be maintained high after the vowel to maximize differences in sonority with the following syllable onset. Following this principle, errors which reduce sonority in the onset – thus increasing the rise in sonority – or increase sonority in coda – thus maintaining high sonority – are simplifications; errors in the opposite direction are complications; errors which do not modify the sonority profile are neutral. We have used the following sonority hierarchy. From less to more sonorous > voiceless stops (p,t,k) > voiced stops (b,d,G), affricates, fricatives, nasals, liquids and glides.

### 6.5.4. Complexity of phonemes in terms of markedness

Phonemes are commonly defined through sets of features representing articulatory characteristics of the sounds to be produced. Here, we limited ourselves to a consideration of features related to timing, place, and manner of production where it is most uncontroversial that one feature value is more difficult or marked compared to another.

a. Timing - *Devoicing errors*. Unvoiced obstruents are easier than voiced counterparts at least for languages like Italian where vibration of the vocal folds has to precede release of the articulatory closure for voiced consonants (see Zmarich and Bonifacio, 2005 for a discussion of the difficulty of voiced consonants in Italian). Therefore, we classified the errors b > p, d > t, G > k, g > c, v > f as simplifications and the opposite errors as complications.

b. Manner - *Stopping errors*. A complete constriction of the vocal tract, such as that involved in the production of stop consonants (also called plosives), can be considered easier than a more limited closure such as that involved in the production of fricative and affricate consonants. Stops, in fact, have a very wide cross-linguistic distribution and are acquired early by children. To use a broader contrast, we considered all errors where fricatives (f,v,s), affricates (tʃ,dʒ,ts,dz), nasals (m,n) and liquids (r,l) were produced as stops (p, t, k, b, d, G) to be simplifications and errors in the opposite direction to be complications.

c. Place - *Fronting errors*. Labial and palatal consonants are easier than velar consonants. Therefore, velar stops produced with a palatal or labial place of articulation (k/G > p,b,t,d) were considered simplifications; the opposite errors as complications.

d. Manner - *Trill neutralizations*. Among liquids, the Italian /r/ is a rhotic sound produced with the tip of the tongue vibrating against the alveolar region. /r/ is usually realized as a tap when short and as a trill when long (e.g., when in a geminate consonant). Rhotic sounds are difficult because the oral configuration and the strength of the air flow must be just right to cause vibration. Therefore, we considered r > l errors simplifications and errors in the opposite direction complications.

When an error has involved changes in multiple features with contrasting outcomes, the majority outcome has been used for an overall classification of the error.

Note that some theorists have assumed that phonological lexical representations are under-specified for some feature values. Unmarked features will be left blank since, in production, they can be filled in with default values. According to under-specification theory, unmarked features/phonemes should be more easily overwritten and substituted with marked features/phonemes. This is the opposite of what is predicted by a tendency to simplify, which predicts fewer, not more, errors with unmarked features/phonemes.

### 6.6. Results

Table 3 shows overall simplification rates across our three production tasks separately and combined together. Simplification measures are based on feature markedness, rather than sonority,

**Table 3**
Mean rate of simplifications (affecting syllables, transitions and phoneme markedness) in repetition, reading and naming. Rates are computed: 1. out of all errors (including substitutions, deletions and insertions but not transpositions since their outcome usually does not modify phonological complexity); 2. Out of simplifications+complications, excluding neutral errors.

| | Apraxic | | | Mixed | | | Phonological | | | $G^2$ | $p$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total $N$ | Mean % | SD | Total $N$ | Mean % | SD | Total $N$ | Mean % | SD | Aprax. vs. Phonol. | |
| **Repetition** | | | | | | | | | | | |
| 1.all errors | 3824 | **54.1** | 10.3 | 813 | **30.4** | 9.4 | 1612 | **29.4** | 5.9 | 34.7 | < **.001** |
| 2.simpl+compl | 2731 | **75.8** | 8.1 | 479 | **51.6** | 8.8 | 1045 | **45.4** | 4.7 | 27.5 | |
| **Reading** | | | | | | | | | | | |
| 1.all errors | 2948 | **53.2** | 19.6 | 544 | **31.8** | 10.5 | 1162 | **20.1** | 14.9 | 14.2 | < **.001** |
| 2.simpl+compl | 2162 | **72.6** | 14.6 | 372 | **46.5** | 12.5 | 547 | **42.8** | 6.7 | 11.4 | |
| **Naming** | | | | | | | | | | | |
| 1.all errors | 874 | **52.9** | 18.5 | 220 | **22.3** | 12.8 | 500 | **21.2** | 12.1 | 12.7 | < **.001** |
| simpl+compl | 692 | **66.8** | 15.0 | 118 | **41.5** | 14.7 | 247 | **42.9** | 15.7 | 18.6 | |
| **Total** | | | | | | | | | | | |
| 1.all errors | 7646 | **53.6** | 14.2 | 1577 | **29.7** | 6.1 | 3274 | **24.9** | 6.7 | | |
| 2.simpl+compl | 5585 | **73.4** | 14.3 | 969 | **48.4** | 8.8 | 1839 | **44.3** | 5.0 | | |

since these are largely overlapping measures (see later). Results are very similar if sonority instead of markedness simplifications are included. Simplification rates have been calculated in two ways: (1) number of simplifications over all errors; (2) number of simplifications over the sum of simplifications and complications, excluding neutral errors. Simplification rates were similar across tasks and the apraxic patients always showed a much stronger tendency to simplify than the phonological patients. Inter-correlations between tasks were high (Pearson r correlations for simplification measure 1: repetition and reading=**.88**; repetition and naming=**.72**; reading and naming=**.74**. Correlations for simplification measure 2: repetition and reading=**.77**; repetition and naming=**.80**; reading and naming=**.92**; all $p < .001$).

Table 4 shows results broken down by different kinds of simplification in repetition, where we have the largest sample of individual errors. With all measures except simplifications of transitions – where significance is marginal due to fewer errors – the apraxic patients made significantly more simplifications than the phonological patients. Therefore, even when markedness simplifications are broken down into different types, the pattern remains very consistent. For all contrasts, except for trill neutralization which has few errors, the apraxic patients made significantly more simplifications than the phonological patients. Note that, here, we are interested in a contrast between patients. Since the stimuli administered were the same across patients with minor exceptions, we can safely compare rates of simplification and complication. Analyses using the percentage out of stimuli in the corpus also always showed significant interactions between the tendency to simplify and patient group.

There were significant inter-correlations between different simplification measures (CV templates and assimilations: Pearson $r=$**.44**, p=.03; CV templates and sonority: $r=$**.36**, $p=$.08; CV templates and markedness: $r=$**.48**, $p=$.02; sonority and markedness: $r=$**.85**, $p < .001$). Moreover, as predicted, each simplification measure, except assimilations which had fewer errors, showed a strong correlation with the rate of phonetic errors (CV templates: $r=$**.61**, $p=$.002; sonority: $r=$**.62**, $p=$.001; markedness: $r=$**.78**, $p < .001$; assimilations: $r=$.21, $p=$.31). Correlations with other characteristics of speech production will be discussed in the last empirical section of the paper.

The fact that both simplification of syllables (CV templates) and simplifications of phonemes (sonority and markedness) correlate with phonetic errors is consistent with the hypothesis that they are also a response to articulatory difficulties. However, it is clear that there is some overlap between groups and variability in the type of deficits suffered by different patients (see Appendices C and D for individual results). For example, patients AV and OB made mostly simplifications of syllable structure, while AM showed stronger simplification of phonemes. Only a few patients made a sizeable number of assimilations (AV, DC, EM and GC). There is also variability in which particular features are simplified. Some patients have specific difficulties with voicing, suggesting difficulties in the timing of the articulators (AM, GC). Voiced consonants are particularly difficult in Italian since vibration of the vocal cords has to start before release of the articulatory closure, unlike in English. Other patients, instead, have more difficulties controlling manner of articulation. They find it easier to produce a complete closure of the articulators as required by stop consonants, compared to the partial closure required by other classes of consonants (AP, AV, MI). Still other patients have particular difficulties in producing trills which require a very precise oral configuration and force in the air flow (EM). These observations show that simplifications take different forms in different patients, but they do not detract from our main finding that there is a strong relation between each of these simplification measures and the rate of phonetic errors.

## 7. Other speech production measures

### 7.1. Word durations

One of the criteria often used to diagnose AoS is a dysfluent speech. As we have already argued, however, measures taken from connected speech are problematic because patients can show between-words disfluencies for a number of different reasons. Another measure used clinically, diadochokinesis, where the patient has to repeat a syllable or word as many times as possible in unit of time, is also problematic since it involves activating over and over again the same speech plan rather than stressing new or challenging computations (see Ziegler, 2002 for possible evidence of no impairment in AoS). As a possibly better measure of fluency, we have used the time taken to produce single words (word durations). We have used this measure to compare groups and to

**Table 4**
Different types of phonological simplification in single word repetition.

| | Apraxic | | | Mixed | | | Phonological | | | $G^2$ | $p$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total N | Mean% simpl | SD | Total N | Mean% simpl | SD | Total N | Mean% simpl | SD | Aprax. vs. Phonol. | |
| 1. Simpl of **Syllables** (del+ins) | 1003 | **74.3** | 11.0 | 191 | **56.0** | 9.4 | 388 | **47.7** | 8.5 | 14.54 | **< .001** |
| 2. Simpl of **Transitions** (geminate err) | 212 | **80.7** | 23.6 | 39 | **69.2** | 22.2 | 78 | **56.4** | 29.2 | 2.82 | **.09** |
| 3. Simpl of Phonemes **Sonority** (substitutions) | 1449 | **72.9** | 15.5 | 224 | **59.4** | 10.6 | 582 | **52.7** | 6.1 | 8.07 | **< .001** |
| 4. Simpl of phonemes **Markedness** (substitutions) | 1516 | **76.1** | 15.7 | 249 | **45.4** | 12.9 | 579 | **42.3** | 7.3 | 18.20 | **< .001** |
| **Simpl of Phon Markedness** | | | | | | | | | | | |
| a. Devoicing | 472 | **88.6** | 28.5 | 98 | **39.8** | 8.1 | 183 | **36.6** | 10.4 | 15.71 | **< .001** |
| b. Stopping | 698 | **69.6** | 18.5 | 102 | **50.0** | 22.8 | 261 | **47.5** | 9.2 | 4.39 | **.04** |
| c. Fronting | 106 | **71.7** | 32.8 | 30 | **43.3** | 30.5 | 65 | **36.9** | 42.2 | 5.64 | **.02** |
| d. Trill neutralizations | 240 | **72.1** | 34.6 | 19 | **52.6** | 36.4 | 70 | **42.9** | 28.2 | 0.86 | .35 |

establish correlations with other characteristics of speech production (see later).

### 7.2. Method

For each patient, we measured 25 correctly produced words and 18 words containing a single error. Since different patients made errors on different words, the same words could not be measured across patients. However, the different word samples were carefully matched for word frequency, word length in terms of number of phonemes and syllables, and phonological complexity. The incorrectly produced words had to contain an error on a single phoneme and had to preserve target length. Outcomes of errors were also matched across samples. The incorrect samples contained 7–8 complications, 7–8 simplifications and 2–4 neutral errors. The same experimental words measured in each patient were given to five control speakers of similar age and education.

### 7.3. Results

Results are reported in Table 5. All patients showed reduced speech rates compared to controls (words correct, $t=3.2–12.0$; $p=.004–<.001$; words with errors, $t=1.9–11.93$; $p=.02–<.001$.). The difference did not reach significance only in two patients (in words correct for MS: $t=.23$; $p=.82$; and in errors for MP; $t=1.9$; $p=.08$). As a group, the apraxic patients took longer than the other two groups, but differences were not always significant (apraxic vs. phonological, word correct: $t=1.52$; $p=.14$; word with errors: $t=1.06$; $p=.30$; apraxic vs. mixed, word correct: $t=4.72$; $p<.001$; word with errors: $t=4.36$; $p<.001$). Moreover, some of the apraxic patients showed relatively fast speech (i.e., AP and SR) and some of the phonological patients long durations (i.e., MC and VS). This illustrates the difficulty of using fluency of speech alone as an indicator of articulatory difficulties, even when fluency is measured in terms of word durations as in our case.

## 8. Consonant/vowel errors across tasks

The difference between consonants and vowels is fundamental

**Table 5**
Production durations in millisec. for words repeated correctly (sample $N=25$) and incorrectly (sample $N=18$) by patients and by a sample of five controls. Words vary across patients, but are the same across patients and controls (see text).

| | Patients | | Controls | | t-test | p |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Patients vs. controls | |
| **Apraxic** | | | | | | |
| Word correct | **1057** | 194 | **623** | 52 | 7.17 | <.001 |
| Range | 719–1378 | | 591–706 | | | |
| Word errors | **1464** | 390 | **735** | 44 | 6.16 | <.001 |
| Range | 930–2155 | | 638–785 | | | |
| **Mixed** | | | | | | |
| Word correct | **761** | 46 | **685** | 16 | 3.11 | .02 |
| Range | 775–793 | | 673–706 | | | |
| Word errors | **939** | 52 | **772** | 12 | 6.28 | .006 |
| Range | 884–988 | | 760–787 | | | |
| **Phonological** | | | | | | |
| Word correct | **909** | 243 | **631** | 41 | 3.39 | .009 |
| Range | 692–1415 | | 597–708 | | | |
| Word errors | **1271** | 427 | **756** | 37 | 3.61 | .007 |
| Range | 847–2000 | | 687–797 | | | |

to speech and there is a clear difference in their ease of articulation. Producing consonants involves more articulators and finer co-ordination and timing than producing vowels. Consistent with this, the first vocalizations of infants involve vowels and vowel sounds are prevalent during the babbling stage (Oller, 1980; Oller et al., 1999; Smith, 1973). Previous studies have reported a high concentration of consonant vs. vowel substitutions in patients with AoS, but a more balanced distribution in patients with PhI (e.g., Burns and Canter, 1977; Monoi et al., 1983; Romani et al., 2011a with an overlapping smaller patient sample[3]), so that a concentration of errors on consonants is considered by some a defining characteristic of AoS (Darley et al., 1975). Finally, error patterns where more errors are made on vowels, have been reported, but in tasks not involving articulation, such as spelling (e.g., Cotelli et al., 2003; Cubelli, 1991), or in patients with fluent speech (three single cases described, respectively, by Caramazza et al., 2000, Romani et al., 1996 and Semenza et al., 2007). This suggests that difficulties of phonological selection can target either type of segment, but that, in apraxic patients, difficulties of articulation produce more sound errors on consonants. Here, we compare rates across groups; correlations with other speech measures will be reported later on.

### 8.1. Results

Results are reported in Table 6. Across spoken tasks, the apraxic patients made significantly higher proportions of errors on consonants than the phonological patients. Correlations across tasks were high (Pearson $r$- repetition and reading$=$**.70**; repetition and naming$=$**.73**; naming and reading$=$**.85**; for all $p<.001$). These results are consistent with consonants being articulatorily more difficult than vowels. It is to be noted, however, that results may be different in other languages and that our analyses are limited to perceptual substitutions. Narrow phonetic analyses may reveal more errors on vowels.

## 9. Correlations among production measures

The previous sections of the paper have demonstrated that, although similar in other respects, patients subdivided on the basis of rates of phonetic errors differ significantly in: (1) rates of phonological simplifications, both syllabic and phonemic; (2) concentrations of errors on consonants. They also differ marginally on signs of bucco-facial apraxia and rates of lexical errors. Instead, they do not differ significantly in overall rate of repetition errors (although the apraxic patients were significantly more impaired in reading and naming) or in word durations. Here, we want to assess how these variables relate to one another, considering the whole group of patients (phonological and apraxic patients taken together) without any a-priori subdivision. In particular, we want to consider whether simplification rates are selectively associated with other characteristics that indicate articulatory difficulties and whether this is independent of severity. We will report correlations using measures from repetition, since this task taps phonological difficulties with less contamination from orthographic or word-retrieval difficulties. However, correlations across output tasks are high and similar results were obtained across tasks.

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[3] Note that Odell et al. (1991) reported similar error rates on consonant and vowels in patients with AoS and CA. In this study, however, using narrow phonetic transcription vowel elongations were included among the errors. Therefore, a tendency to make fewer vowel substitutions in the apraxic patient will have been offset by a tendency to produce more vowel elongations resulting in no overall difference between the groups.

**Table 6**
Number and rates of consonant substitutions across tasks. Rates are computed out of total substitutions.

| | Apraxic | | | Mixed | | | Phonological | | | G | p |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *N* | % cons | SD | *N* | % cons | SD | *N* | % cons | SD | Aprax. vs. Phonol. | |
| **Repetition** | 2428 | **92.1** | 6.3 | 403 | **66.0** | 10.1 | 971 | **78.4** | 17.1 | 6.01 | **.01** |
| **Reading** | 1847 | **81.4** | 15.6 | 254 | **68.1** | 23.0 | 518 | **57.1** | 19.2 | 6.43 | **.01** |
| **Naming** | 540 | **84.8** | 9.9 | 87 | **50.3** | 23.0 | 215 | **56.7** | 17.8 | 11.13 | **< .001** |
| **Total** | 4815 | **86.9** | 9.9 | 744 | **64.3** | 11.5 | 1704 | **67.5** | 16.2 | 8.07 | **.004** |

## 9.1. Results

Correlations are reported in Table 7. Results partialling out severity in terms of overall rate of incorrect words in repetition were very similar, so only bivariate correlations are reported. Simplification rates were strongly related to other measures of motor/articulatory impairment: bucco-facial apraxia (**.81**), phonetic errors (**.88**) and rate of consonant substitutions (**.59**). Instead, the tendency to simplify and the tendency to make errors on consonants were not significantly related to overall severity (**.32** and **.14**). This is important since it demonstrates that qualitative differences between patients were not simply the consequence of different degrees of severity. Finally, although correlations with rate of lexical errors were generally not significant, it is interesting that they are all negative, consistent with the hypothesis that they reflect difficulties at another processing level.

In contrast, fluency (measured by correct and incorrect word durations) was associated both with overall error rates (**.61–.57**) and with rate of phonetic errors (**.52–.42**). This is expected since all of these measures reflect severity of impairment. More severe patients will make more errors and have more dysfluent speech. Word durations, instead, were less related to qualitative patterns such as the proportion of simplifications and consonant errors (with correlations ranging from .23 to .42). The correlations with bucco-facial apraxia were also relatively low (.41–.37). These results indicate that word durations are not selectively associated with articulatory difficulties. Instead, it is possible that patients with articulatory difficulties use slowing down of speech and simplifications as alternative coping strategies. Patients with a high rate of phonetic errors are generally slow, but there are also patients with high rate of phonetic errors who are relatively fast and make simplifications to cope with their difficulties. Conversely, among patients with a low rate of phonetic errors and no tendency to simplify there are some patients with slow word production, who are likely to be slow because they have trouble accessing phonemes and not because they have difficulties in computing articulatory plans.

## 10. Cluster analyses

Finally, we run two hierarchical cluster analyses using the Ward method and squared Eucledian distance on *z*-scores to group patients in either two or three clusters. We entered the following variables: (1) rate of phonetic errors, (2) rate of simplifications, (3) rate of consonant errors, and (4) durations of word correct, all

**Table 7**
Pearson *r* two-tailed correlations between different characteristics of single word repetition. Correlations significant after Holm–Bonferroni correction for multiple comparisons are in bold. All measures, but for bucco-facial apraxia are from word repetition. Simplifications are computed out of simplifications+complications (leaving out neutral errors). Consonant error rate refer to rate of consonant substitutions over consonant+vowel substitutions. Lexical error rate refer to rate of lexical errors over total errors.

| | | Simpl vs. compl | Bucco-facial apraxia | Phonetic rate | Cons rate | Lexical rate | Word-correct durations | Word-error durations |
|---|---|---|---|---|---|---|---|---|
| Simplifications | *r* | 1 | | | | | | |
| | Sig. | | | | | | | |
| Bucco-facial apraxia | *r* | **0.81** | 1 | | | | | |
| | Sig. | *< .001* | | | | | | |
| Phonetic err. rate | *r* | **0.88** | **0.81** | 1 | | | | |
| | Sig. | *< .001* | *< .001* | | | | | |
| Consonant err rate | *r* | **0.59** | 0.43 | 0.48 | 1 | | | |
| | Sig. | *0.002* | *0.05* | *0.02* | | | | |
| Lex. err rate | *r* | − 0.35 | − 0.25 | − 0.45 | − 0.43 | 1 | | |
| | Sig. | *0.09* | *0.3* | *0.03* | *0.04* | | | |
| Word-correct durations | *r* | 0.42 | 0.41 | 0.52 | 0.23 | − 0.36 | 1 | |
| | Sig. | 0.04 | 0.06 | 0.009 | *0.27* | *0.08* | | |
| Word-error durations | *r* | 0.36 | 0.37 | 0.42 | 0.33 | − 0.39 | **0.94** | 1 |
| | Sig. | *0.09* | *0.1* | *0.04* | *0.12* | *0.06* | 0 | |
| Overall errors | *r* | 0.32 | 0.3 | 0.42 | 0.18 | − 0.21 | **0.61** | 0.57 |
| | Sig. | *0.13* | *0.19* | *0.04* | *0.4* | *0.31* | *0.001* | *0.004* |

taken from word repetition. We did not use bucco-facial apraxia scores because there is no variation beyond the apraxic group. Note that twenty-four cases for four variables is above the recommended minimum (rule of thumb $2^k = 16$; $k$ = number of variables; Dolnicar, 2002), but below optimal number ($= 2^k * 5$), thus results should be considered with caution.

A subdivision into two clusters sub-grouped on one side the patients which we originally categorized as *apraxic*, and on the other the *phonological* and *mixed* patients. The categorization into three groups is more interesting. Results are reported in Table 8 which shows means for all the variables used for the cluster analyses together with means for two evaluative variables in which groups may be expected to differ: rate of lexical errors and score on bucco-facial apraxia, plus a general severity variable such as rate of words repeated correctly.

Again, the original apraxic group is maintained; these are patients who make a lot of phonetic errors and simplifications and with generally, but not always, slow speech. The third group is made of patients with (relatively) fast speech, very few phonetic errors and simplifications and high rates of lexical errors. These are patients who suffer from phonological, but not apraxic difficulties. Group 1 and 3 differ significantly for all variables except the ones linked to overall severity. Finally, the intermediate, mixed group (phon2 in the table) is made of patients with low rates of phonetic errors and simplifications (both significantly different from group 1), but slower speech and low rates of lexical errors (significantly different from group 3). The level of impairment in these patients is more difficult to establish. However, since they make a large number of sound errors, but few phonetic errors and phonological simplifications, it is likely that they suffer from difficulties of phonological selection, as group 3, but that, for them,

this process is slow as well as error prone. Overall, these statistical analyses confirm the conclusions of the previous sections: durations by themselves are relatively uninformative because patients who are slow or relatively fast, do not systematically differ for other speech characteristics.

## 11. General discussion

We looked at the speech characteristics of a group of 24 Italian patients with aphasia who make a large number of sound errors in production tasks. We originally subdivided the patients into groups on the basis of number of phonetic errors and identified a number of variables where performance differed. These variables included several measures of simplification including simplifications of syllable structure and simplifications of phonemes, measured in terms of a number of featural contrasts. Across voicing, manner and place of articulation, the apraxic patients systematically showed a strong tendency to simplify in contrast with the phonological patients.

Finally, we looked at correlations between a composite simplification measure and other variables characterizing speech production. We found that: (1) *severity of bucco-facial apraxia*; (2) *frequency of phonetic errors*; (3) *rate of substitutions on consonants relative to vowels* were inter-correlated and strongly related to (4) *simplification measures*. This pattern of associations is theoretically coherent since all these variables are related to difficulties in articulatory planning. Phonetic errors indicate a difficulty producing target oral configurations, consonants are more difficult to articulate than vowels and simplifications produce syllables and phonemes which are easier to articulate. This pattern of

**Table 8**
Patient categorization following a hierarchical cluster analysis returning 2 or 3 clusters.

| | Orig class | 2 clusters | 3 clusters | Simpl Out sim+com | Speed ms Word correct | Phonet err % | Cons err % | Lexical err % | Bucco-facial apraxia N err/20 | % word corr out of stim |
|---|---|---|---|---|---|---|---|---|---|---|
| AM | Apr | 1 | Aprax | 88.1 | **1378** | 25.4 | 91.8 | 14.5 | 6 | 43.7 |
| AP | Apr | 1 | Aprax | 75.2 | **719** | 12.4 | 91.4 | 5.9 | 2 | 75.9 |
| AV | Apr | 1 | Aprax | 70.6 | **916** | 21.3 | 90.7 | 7.7 | 4 | 48.0 |
| DC | Apr | 1 | Aprax | 65.3 | **1170** | 13.7 | 94.5 | 10.8 | 3 | 6.5 |
| DG | Apr | 1 | Aprax | 69.3 | **1230** | 13.3 | 89.1 | 4.5 | 0 | 51.6 |
| EM | Apr | 1 | Aprax | 79.0 | **929** | 16.4 | 97.7 | 5.6 | 4 | 8.9 |
| GC | Apr | 1 | Aprax | 85.7 | **1116** | 14.1 | 94.2 | 6.0 | 8 | 63.1 |
| MI | Apr | 1 | Aprax | 81.8 | **1075** | 24.0 | 96.9 | 7.1 | 8 | 58.3 |
| OB | Apr | 1 | Aprax | 64.9 | **1123** | 16.4 | 79.1 | 6.1 | – | 51.6 |
| PV | Apr | 1 | Aprax | 69.8 | **1164** | 17.2 | 82.6 | 19.3 | 8 | 43.8 |
| SR | Apr | 1 | | 69.3 | **812** | 10.2 | 88.7 | 6.5 | 4 | 74.3 |
| | | | Mean | **74.5** | **1057.4** | **16.8** | **90.6** | **8.6** | **4.7** | **47.8** |
| | | | | | | | | | | |
| DS | Phon | 2 | Phon2 | 54.1 | **900** | 3.3 | 84.5 | 13.7 | 0 | 70.2 |
| GM | Phon | 2 | Phon2 | 40.8 | **851** | 1.8 | 81.9 | 8.6 | 0 | 83.4 |
| LB | Phon | 2 | Phon2 | 44.7 | **832** | 4.5 | 71.4 | 7.5 | 0 | 89.7 |
| MC | Phon | 2 | Phon2 | 43.8 | **1210** | 3.9 | 98.8 | 8.3 | 0 | 22.5 |
| RM | Phon | 2 | Phon2 | 38.9 | **734** | 2.4 | 88.5 | 3.1 | 0 | 83.1 |
| VS | Phon | 2 | Phon2 | 46.3 | **1415** | 4.9 | 60.3 | 12.2 | 1 | 25.8 |
| | | | Mean | **44.8** | **990.5** | **3.5** | **80.9** | **8.9** | **0.2** | **62.4** |
| | | | *t*-test (2 vs. 1) | **<.001** | 0.56 | **<.001** | **0.05** | 0.87 | **<.001** | 0.28 |
| | | | *t*-test (2 vs. 3) | 0.25 | **0.04** | **0.63** | 0.31 | **<.001** | 0.90 | 0.85 |
| | | | | | | | | | | |
| AG | Mix | 2 | Phon | 62.1 | **775** | 7.1 | 81.0 | 24.7 | 0 | 60.7 |
| CA | Mix | 2 | Phon | 44.7 | **793** | 6.3 | 77.6 | 21.8 | 0 | 75.0 |
| MS | Mix | 2 | Phon | 42.5 | **693** | 5.4 | 64.7 | 19.5 | – | 70.0 |
| PM | Mix | 2 | Phon | 51.0 | **783** | 8.2 | 61.9 | 14.8 | – | 27.8 |
| AC | Phon | 2 | Phon | 48.4 | **766** | 1.1 | 90.2 | 29.1 | 0 | 76.9 |
| MP | Phon | 2 | Phon | 50.0 | **692** | 0.5 | 77.7 | 41.0 | 1 | 74.1 |
| TC | Phon | 2 | | 43.5 | **782** | 0.8 | 63.4 | 33.8 | 0 | 71.3 |
| | | | Mean | **48.9** | **754.7** | **4.2** | **73.8** | **26.4** | **0.2** | **65.1** |
| | | | *t*-test (1 vs. 3) | **<.001** | **<.001** | **<.001** | **<.001** | **<.001** | **<.001** | 0.10 |

associations is especially interesting since it is not mediated by differences in severity. Simplifications and consonant error rates are relative distributions and not absolute rates which would be inevitably linked to severity. In fact, in our sample, these measures were unrelated to (a) word durations and (b) overall errors in repetition. The selectivity of the correlations between variables linked to articulation is underscored by the fact that correlations with a variable tapping difficulties at another level – rate of lexical errors – were systematically negative. Finally, the results of a cluster analysis confirmed a grouping of (apraxic) patients on the basis of high rates of simplifications, phonetic errors and consonant errors, but created two groups for the other patients on the basis of word duration and rates of lexical errors. One group (phonological 2) had slower speech and fewer lexical errors underscoring the point that difficulties of phonological selection can also slow down speech in some patients. Our results have important implications.

### 11.1. Implications for linguistic theories

The universality of principles of complexity has often been motivated through the universality of the human articulatory apparatus. According to this view, simpler segments are more common in the languages of the world and are produced first by children because they are easier to articulate (see Bermúdez-Otero and Börjars, 2006; Kingston, 2007; Ohala, 1997, 1999). Not everybody, however, has endorsed this view and others have considered markedness principles to be abstract and related to the structure of phonological representations (e.g., Jakobson, 1941; Hale and Reiss, 2000). Our results provide strong evidence for the first position since complexity principles determine performance in patients with associated articulatory difficulties, but not in patients with other types of phonological difficulties. In a way similar to us, Nespoulous et al. (1987) showed phonemically closer errors and stronger markedness effects in the substitution errors made in word repetition and reading by Broca's aphasics compared to conduction aphasics. They characterized the speech of the Broca's aphasics as disfluent and marked by '*a phonetic disintegration syndrome*' as described by Alajouanine and Lhermitte (1960) to indicate AoS. Also similar to us, they speculated on the possible causal association between phonetic impairments and markednes effects, but this went against the views prevalent at the time which saw markedness effects as an abstract property of linguistic representations. A correspondence between markedness effects and phonenetic errors, instead, is perfectly in tune with most current versions of Optimality Theory which see markedness grounded in articulation (e.g., de Lacy, 2006; Ohala, 1997; Prince and Smolensky, 2004).

The fact that complexity principles do not operate across levels may come as a surprise. One may expect that unmarked features will be more resilient to brain damage and more easily accessed than marked features across impairments. However, one should consider that phonological impairments may involve difficulties in *selecting* the right phoneme from alternatives rather than degradation of representations. In this case, errors may be affected by the similarity among alternatives, but not by the complexity of the target, with a resulting lack of directionality in the errors (for a similar lack of directionality in the lexical-semantic domain see Jefferies and Lambon Ralph, 2006). Consistent with our findings, Shattuck-Hufnagel and Klatt (1979) reported no tendency to simplify in the speech errors of adult controls with fluent speech. Also Ash et al. (2010) found no markedness effects in patients with progressive aphasia that they described as non-fluent, but who showed no evidence of articulatory difficulties (e.g., few phonetic errors, high rates of vowel errors).

### 11.2. Implications for model of speech production

Traditionally, speech production models have endorsed a strict division between a phonological processing stage – where the phonemes corresponding to words are selected – and a subsequent processing stage where sequences of phonemes are translated into integrated articulatory plans/programs. This translation process, moreover, is supposed to occur on line, on the basis of the application of a set of rules linking abstract phonemes to corresponding motor actions. A number of empirical and theoretical developments, however, have weakened this position and lead to an increased interest in the way these two processing levels interact. As already mentioned in the Introduction, the view of strict seriality between stages has been questioned by the finding that sound errors – whether induced in the laboratory or collected in more ecological conditions – rarely are canonical phonological errors.

For example, in tongue twister, the articulations of target phonemes is influenced by competing phonemes so that either intermediate parameters are used (see, McMillan and Corley, 2010), or, when compatible, simultaneous gestures appropriate for multiple phonemes are carried out (such as rising both the tip and dorsum of the tongue in the production of pairs such as top-cop; see Pouplier and Goldstein, 2010). This shows that competition for selection is not always resolved at the phonological level *before* phonetic selection takes place. Instead, activation at the phonological level *cascades* to the phonetic level with multiple phonemes influencing phonetic selection. The distinction between a *phonological level* involving *stored representations* and a *phonetic level* involving *translation procedures* has also been weakened. For example, it has been shown that relatively few exposures to pronunciations of low-frequency words can modulate the way these words are pronounced (e.g., Goldinger, 1998). Goldrick et al. (2011) have shown that low-frequency words – which have stronger, more narrowly defined phonetic representations – leave stronger traces of target phonemes in the errors than high-frequency words. These influences will be possible only if the phonetics of the low-frequency words is stored and able to modulate subsequent production or the effect of errors. These results are in tune with approaches, such as articulatory phonology, which see phonological features expressed in terms of motor targets (e.g., Browman and Goldstein, 1992) and may induce the radical view that there is only a single processing level with no distinction between phonology and phonetics (Baese-Berk and Goldrick, 2009; Frisch and Wright, 2002; McMillan et al., 2009). Even some exemplar models where phonetic processing is based on accessing stored phonetic exemplars, however, have maintained a phonological symbolic level (e.g., see Pierrehumbert, 2002).

The role of a symbolic phonological level is difficult to dismiss. In all languages, lexicons are made by recombining twenty or thirty discreet phonemes into hundreds of thousands of words. Having a small number of building blocks not only helps with word formation and acquisition of new words, but also with perceptual identification, storage and error monitoring. Moreover, phonetic representations have to take into account context and the particular requirements of individual utterances. This is why the exemplar model of Pierrehumbert (2002), for example, assumes that clouds of stored phonetic exemplars are associated with *phonological labels* (i.e., phonological symbolic labels linked to phonetic features). Furthermore, it assumes that phonological representations are held in a phonological buffer where parameters related to clarity, speed, register, and prosodic emphasis are set and used to address different regions of phonetic space (e.g., vowels timing may be longer, for more formal/clearer speech). Our results sit well with such a model and, more generally, contribute to elucidate the relation between phonological and phonetic

representations by showing both their independence and their interactions.

We have shown different patterns of errors. In one group of patients, errors do not systematically result in simplifications and are best interpreted as *errors of selection*. Lexical phonological representations are disrupted so that links between words and phonemes are weakened or there is increased noise (e.g., Foygel and Dell, 2000; Rapp and Goldrick, 2000; Schwartz et al., 2006). This allows stronger competition from intruding phonemes which activate corresponding phonetic representations that are produced instead of targets. Consistent with a source at the phonological symbolic level, selection errors are more influenced by word frequency (see, Romani and Galluzzi, 2005), are more associated with lexical errors, and produce phonemes more distant from the target (sharing fewer features). In a second group of patients, instead, sound errors are phonemically closer to the target and produce systematic simplifications: complex onsets and codas are reduced and marked features are realized as unmarked. We assume these errors to arise more peripherally, *in articulatory planning*. Resource limitations may not allow a plan with the right level of complexity to be specified in a reasonable time. This may hold true even if word-sized phonetic programs are stored because complex programs may exceed available computational space. Simplifications may occur directly on the unfolding articulatory plans, but this seems unlikely. Simplifications involve clear-cut and profound modifications of the target phonology. Moreover, if revisions would occur at such late stage, they should result in dysfluencies, but we failed to find a systematic association with word durations. Instead, although simplifications are motivated by articulatory difficulties, they could be triggered at an earlier stage where other utterance-specific parameters are also set. Depending on what kind of register the speaker wants to use, buffered phonological representations may access different kinds of phonetic representations. Similarly, a limitation in computational resources following brain-damage may trigger simplifications because parameters which involve fewer resources are set. Assuming that simplifications are triggered at this earlier stage, also well explains the trade-offs between speed, simplification rates and phonetic accuracy demonstrated by our patients (see for example in Table 8, among the apraxic patients, the case of EM with high rates of simplifications but relatively fast speech contrasting with the case of OB with fewer simplifications, but slower speech).

A model that has a single phonological (or phonetic) level before motor implementation cannot explain our results. If simplifications arise from a phonological impairment this will leave unexplained why other patients making sound errors do not show this tendency. If they arise from a low level motor impairment, this will leave unexplained differences from dysarthria. Instead, simplifications are best explained as arising at an intermediate level where an articulatory plan for the utterance is computed (see also Buchwald and Miozzo, 2011 for differences in the nature of sound errors). While our results point to distinct levels, they are also consistent with close interactions. Previous studies have shown that difficulties of phonological selection cascade to influence phonetic realization, here we have shown that difficulties at the phonetic level may influence parameters set at a prior phonological level.

### 11.3. Implications for the diagnosis of AoS

Different patterns of sound errors linked to different processing levels legitimize AoS as an independent disorder between phonology and motor realization. They also suggest new ways to characterize it by focusing on the qualitative characteristics of speech errors and not on the fluency of speech. Phonological simplifications will indicate articulatory difficulties even in patients who, otherwise, may be identified as suffering solely from phonological deficits. Speech fluency, instead, may depend on the strategy used by the patient to cope with his/her difficulties and be orthogonal to the impairment type. A preponderance of consonant errors is also associated with apraxic difficulties. This pattern is not as distinctive as a tendency to simplify because it is widespread across patients. The opposite, however, is diagnostic: a more balanced distribution of errors between consonants and vowels can be taken as a sign of phonological, non-apraxic difficulties.

More generally, our results indicate the benefits of using a bootstrap approach to investigate post-lexical speech production impairments, where patient classification is not determined, a priori, on the basis of clinical observations, but after quantitative analyses of speech. Types of errors should be part of these analyses. This may seem daunting. However, word repetition tasks are quick and easy to administer, all patients with post-lexical disorders make individual sound errors which may be unequivocally categorized as simplifications on the basis of clear criteria and new computational tools could be deployed to automatize error analyses in the future.

### 11.4. Implications for rehabilitation

A better diagnostic categorization on the basis of error analyses should result in better, more focused rehabilitation practices. Patients with fluent speech who make high proportions of sound errors are typically treated with some kind of phonological–lexical therapy. Often, this requires the production of spoken words (through repetition, reading, picture naming; see Kohn et al., 1990; Boyle, 1989; Beard and Prescott, 1991; Miceli et al.,1996; Basso et al., 2001), but there are also approaches which focus on retrieving the phonology of words without any overt production (see Davis et al., 2009; Franklin et al., 2002; Waldron et al., 2011a,b), and still other approaches that use the production of written words to help to re-instantiate corresponding, degraded phonological representations (see Jackson-Waite et al., 2003). Our results suggest that patients who make sound errors with a high rate of simplifications are apraxic and will not benefit from tasks which do not involve spoken production, but, instead, will benefit more from therapies with an articulatory-kinematic focus. The lack of good diagnostic criteria may, indeed, be the reason why treatments of phonological disorders have had very variable outcomes (see Kendall et al., 2008; Franklin et al., 2002; Waldron et al., 2011a,b).

Finally, while we have stressed associations in our results, considering variability is also important. Patients varied in the particular articulatory difficulties they displayed. Some had more trouble with timing (producing a majority of devoicing errors), others with controlling manner of articulation (producing a majority of stopping errors), and still others with realizing transitions between consonants (resulting in assimilations and/or simplifications of syllable structure). Again, careful error analyses will be crucial to more effectively direct rehabilitation efforts.

## 12. Conclusions

Distinguishing different types of post-lexical production impairments in aphasia is difficult because of overlapping characteristics across impairments. Both the speech of patients with phonological difficulties (often classified as Conduction and Wernicke aphasics) and the speech of patients with AoS are characterized by large numbers of sound errors, while both the speech of patients with AoS and the speech of patients with dysarthria are characterized by phonetic errors. In all of these impairments,

moreover, speech can be dysfluent because different problems in selecting phonemes, planning gestures and activating the right speech muscles (and taking advantage of proprioceptive feedback) can all slow speech down. Our results have identified a high rate of simplifications as a diagnostic characteristic specific to AoS and a high rate of vowel errors as an indication of difficulties in phoneme selection. These results have implications for the clinical management of AoS, but also strong theoretical implications. Through their selective association with AoS, phonological simplifications show that principles of complexity have their root in articulation and validate a processing model with a level of articulatory planning susceptible to resource limitations and intermediate between phoneme selection and motor implementation. Future studies should continue to explore the relation between different manifestations of articulatory difficulties and possible trade-offs.

## Appendix A

see Table A1.

## Appendix B

see Table B1.

## Appendix C

see Table C1.

**Table A.1**
Patients clinical description according to spontaneous speech. Note: phonological paraphasias characterize the speech of all patients.

| | | |
|---|---|---|
| **APRAXIC** | **AM** | Mildly dysfluent; agrammatic; mild articulatory effort; anomic. |
| | **AP** | Fluent with a fast speech rate which gives to his speech a 'drunken' quality; good sentence construction. |
| | **AV** | Fluent with a fast speech rate which gives to his speech a 'drunken' quality (similar to AP); mildly agrammatic; shows a tendency to initiate utterances with vowels. |
| | **DC** | Dysfluent; agrammatic; severely anomic with use of stereotyped phrases; articulatory effort and syllabification. |
| | **DG** | Dysfluent, slow speech rate; severe articulatory effort; phonetic distortions and syllabification. |
| | **EM** | Global aphasic; spontaneous speech almost absent, reduced to stereotyped utterances; syllabification. |
| | **GC** | Dysfluent; articulatory effort; syllabification and phonetic distortions. |
| | **MI** | Dysfluent; severely agrammatic; severe articulatory effort. |
| | **OB** | Dysfluent; slow speech rate; severely agrammatic; articulatory effort; semantic errors and anomic pauses. |
| | **PV** | Dysfluent; severely agrammatic; mild articulatory effort; severely anomic. |
| | **SR** | Dysfluent; slow speech rate; long pauses between words due to both inertia and difficulty to find words; mildly agrammatic; mild articulatory effort. |
| **MIXED** | **AG** | Fluent; severely impaired organization of discourse; semantic errors and anomic pauses. |
| | **CA** | Fluent; mild impaired organization of discourse; semantic errors and anomic pauses. |
| | **MS** | Fluent but with mildly slow speech rate; pauses between words due to both mild articulatory efforts and anomic pauses; semantic errors; anomic. |
| | **PM** | Fluent but almost unintelligible due to disorganization of discourse and numerous phonemic and lexical paraphasias. |
| **PHONOLOGICAL** | **AC** | Fluent with normal speech rate and good sentence construction. |
| | **DS** | Fluent but with mildly slow speech rate; mildly jargonaphasic; lexical paraphasias. |
| | **GM** | Fluent with normal speech rate and good sentence construction; anomic pauses. |
| | **LB** | Fluent but with mildly slow speech rate; mildly anomic. |
| | **MC** | Dysfluent; very slow speech with hesitations, false starts, long pauses and segment prolongations; conduite d'approche; anomic; lexical paraphasias. |
| | **MP** | Fluent with normal speech rate and good sentence construction (similar to AC). |
| | **RM** | Dysfluent; slow speech rate with hesitations, false starts and long pauses; anomic; lexical paraphasias. |
| | **TC** | Mildly slow speech rate due to hesitations; mildly impaired sentence construction; anomic. |
| | **VS** | Mildly slow speech rate; mildly impaired sentence construction; mildly anomic. |

**Table B1**
Performance in neuropsychological assessment tasks; n.t. = patient not tested because the task is too difficult; - = task not administered. Logistic regressions compare the Apraxic group and the Phonological group.

| | | Phonological Input | | | | | | | | | | | |
| | | Same/diff Syllables (N=60) | | Same/diff Words (N=120) | | Lexical Decision (N=80) | | Word-picture Matching (N=40) | | | | Sentence-picture Matching (N=60) | | Bucco-facial Apraxia (N=20) |
| | | | | | | | | Phonol. foil | | Sem. foil | | | | |
| | | N corr | % | N corr | % | N corr | % | N corr | % | N corr | % | N corr | % | N corr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Apraxic | AM | 52 | **87** | 111 | **93** | 79 | **99** | 20 | **100** | 20 | **100** | 55 | **92** | 14 |
| | AP | 60 | **100** | 120 | **100** | 74 | **93** | 20 | **100** | 20 | **100** | 58 | **97** | 18 |
| | AV | 60 | **100** | 115 | **96** | 80 | **100** | 19 | **95** | 20 | **100** | 52 | **87** | 16 |
| | DC | 56 | **93** | 105 | **88** | 71 | **89** | 17 | **85** | 18 | **90** | n.t | n.t | 17 |
| | DG | 60 | **100** | 120 | **100** | 80 | **100** | 20 | **100** | 20 | **100** | 60 | **100** | 20 |
| | EM | n.t | n.t | n.t | n.t | n.t | n.t | 18 | **90** | 17 | **85** | n.t | n.t | 16 |
| | GC | 60 | **100** | 120 | **100** | 80 | **100** | 20 | **100** | 20 | **100** | 60 | **100** | 12 |
| | MI | 60 | **100** | 116 | **97** | 76 | **95** | 20 | **100** | 20 | **100** | 47 | **78** | 12 |
| | OB | 48 | **80** | – | – | 74 | **93** | 19 | **95** | 20 | **100** | 53 | **88** | – |
| | PV | 51 | **85** | 105 | **88** | 66 | **83** | 20 | **100** | 20 | **100** | 53 | **88** | 12 |
| | SR | 59 | **98** | 119 | **99** | 76 | **95** | 20 | **100** | 19 | **95** | 59 | **98** | 16 |
| Mixed | AG | 54 | **90** | 104 | **87** | – | – | 17 | **85** | 20 | **100** | 48 | **80** | 20 |
| | CA | 45 | **75** | 49 | **41** | – | – | 18 | **90** | 20 | **100** | – | – | 20 |
| | MS | 46 | **77** | 112 | **93** | 75 | **94** | 18 | **90** | 19 | **95** | 48 | **80** | – |
| | PM | n.t | n.t | n.t | n.t | n.t | n.t | n.t | n.t | n.t | n.t | n.t | n.t | n.t |
| Phonological | AC | 52 | **87** | 111 | **93** | 70 | **88** | 18 | **90** | 20 | **100** | 39 | **65** | 20 |
| | DS | 58 | **97** | 119 | **99** | 77 | **96** | 20 | **100** | 20 | **100** | 52 | **87** | 20 |
| | GM | 60 | **100** | 110 | **92** | 75 | **94** | 20 | **100** | 20 | **100** | 56 | **93** | 20 |
| | LB | 60 | **100** | 117 | **98** | 80 | **100** | 20 | **100** | 20 | **100** | 59 | **98** | 20 |
| | MC | 55 | **92** | 115 | **96** | 62 | **78** | 14 | **70** | 20 | **100** | 48 | **80** | 20 |
| | MP | 55 | **92** | 112 | **93** | 61 | **76** | 18 | **90** | 19 | **95** | 55 | **92** | 19 |
| | RM | 60 | **100** | 111 | **93** | 80 | **100** | 20 | **100** | 20 | **100** | 58 | **97** | 20 |
| | TC | 60 | **100** | 120 | **100** | 76 | **95** | 19 | **95** | 20 | **100** | 43 | **72** | 20 |
| | VS | 53 | **88** | 113 | **94** | 78 | **98** | 19 | **95** | 20 | **100** | – | – | 19 |
| $G^2$ | | | 0.01 | | 0.00 | | 0.18 | | 0.09 | | 0.03 | | 0.66 | 2.91 |
| P | | | .93 | | .96 | | .66 | | .77 | | .85 | | .41 | **.09** |

**Table C1**
Different types of simplification errors in single word repetition. Logistic regressions compare rates of simplifications in the ph-Apraxic group and in the ph-Selection group.

| | | 1. Deletions/Insertion changing CV templates | | | 2. Assimilations/Creation of Hetero-syllabic Clusters | | | 3. Substitutions affecting Sonority Contour | | | 4. Neutralization of marked features | | |
| | | Sim N | Com N | Sim % | Sim N | Com N | Sim % | Sim N | Com N | Sim % | Sim N | Com N | Sim % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Apraxic | AM | 40 | 25 | **61.5** | 2 | 2 | **50.0** | 130 | 12 | **91.5** | 218 | 8 | **96.5** |
| | AP | 33 | 10 | **76.7** | 5 | 1 | **83.3** | 64 | 9 | **87.7** | 65 | 23 | **73.9** |
| | AV | 107 | 19 | **84.9** | 22 | 0 | **100.0** | 54 | 50 | **51.9** | 49 | 55 | **47.1** |
| | DC | 62 | 17 | **78.5** | 29 | 3 | **90.6** | 90 | 60 | **60.0** | 63 | 62 | **50.4** |
| | DG | 65 | 42 | **60.7** | 17 | 11 | **60.7** | 90 | 30 | **75.0** | 83 | 20 | **80.6** |
| | EM | 158 | 20 | **88.8** | 31 | 8 | **79.5** | 216 | 101 | **68.1** | 241 | 86 | **73.7** |
| | GC | 59 | 12 | **83.1** | 37 | 0 | **100.0** | 110 | 32 | **77.5** | 119 | 24 | **83.2** |
| | MI | 69 | 32 | **68.3** | 1 | 3 | **25.0** | 145 | 11 | **92.9** | 146 | 13 | **91.8** |
| | OB | 80 | 34 | **70.2** | 8 | 8 | **50.0** | 37 | 45 | **45.1** | 45 | 30 | **60.0** |
| | PV | 37 | 31 | **54.4** | 15 | 3 | **83.3** | 84 | 27 | **75.7** | 75 | 21 | **78.1** |
| | SR | 35 | 16 | **68.6** | 4 | 2 | **66.7** | 36 | 16 | **69.2** | 49 | 21 | **70.0** |
| | Total | 745 | 258 | **74.3** | 171 | 41 | **80.7** | 1056 | 393 | **72.9** | 1153 | 363 | **76.1** |
| Mixed | AG | 29 | 13 | **69.0** | 13 | 2 | **86.7** | 48 | 19 | **71.6** | 48 | 40 | **54.5** |
| | CA | 26 | 22 | **54.2** | 5 | 4 | **55.6** | 21 | 21 | **50.0** | 15 | 31 | **32.6** |
| | MS | 20 | 13 | **60.6** | 1 | 2 | **33.3** | 22 | 23 | **48.9** | 13 | 31 | **29.5** |
| | PM | 32 | 36 | **47.1** | 8 | 4 | **66.7** | 42 | 28 | **60.0** | 37 | 34 | **52.1** |
| | Total | 107 | 84 | **56.0** | 27 | 12 | **69.2** | 133 | 91 | **59.4** | 113 | 136 | **45.4** |
| Phonological | AC | 21 | 14 | **60.0** | 2 | 6 | **25.0** | 30 | 16 | **65.2** | 23 | 29 | **44.2** |
| | DS | 22 | 18 | **55.0** | 2 | 4 | **33.3** | 29 | 27 | **51.8** | 35 | 28 | **55.6** |
| | GM | 11 | 10 | **52.4** | 5 | 2 | **71.4** | 23 | 18 | **56.1** | 13 | 30 | **30.2** |
| | LB | 8 | 10 | **44.4** | 1 | 2 | **33.3** | 9 | 9 | **50.0** | 12 | 14 | **46.2** |
| | MC | 49 | 62 | **44.1** | 13 | 12 | **52.0** | 123 | 122 | **50.2** | 96 | 129 | **42.7** |
| | MP | 15 | 10 | **60.0** | 1 | 0 | **100.0** | 20 | 22 | **47.6** | 12 | 18 | **40.0** |
| | RM | 10 | 19 | **34.5** | 1 | 1 | **50.0** | 32 | 20 | **61.5** | 24 | 35 | **40.7** |
| | TC | 15 | 15 | **50.0** | 1 | 5 | **16.7** | 13 | 11 | **54.2** | 14 | 19 | **42.4** |
| | VS | 34 | 45 | **43.0** | 18 | 2 | **90.0** | 28 | 30 | **48.3** | 16 | 32 | **33.3** |
| | Total | 185 | 203 | **47.7** | 44 | 34 | **56.4** | 307 | 275 | **52.7** | 245 | 334 | **42.3** |
| $G^2$ | | | | 14.54 | | | 2.82 | | | 8.07 | | | 18.2 |
| p | | | | **< .001** | | | **.09** | | | **< .001** | | | **< .001** |

**Table D1**
Substitutions involving neutralization of marked features in Single word repetition. Logistic regressions compare rates of simplifications in the ph-Apraxic group and in the ph-Selection group.

| | | 1. Devoicing | | | 2. Stopping | | | 3. Fronting | | | 4. Trill neutralization | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Simp N | Comp N | Simp % | Simp N | Comp N | Simp % | Simp N | Comp N | Simp % | Simp N | Comp N | Simp % |
| Apraxic | AM | 119 | 1 | **99.2** | 5 | 6 | **45.5** | 2 | 1 | **66.7** | 92 | 0 | **100.0** |
| | AP | 19 | 4 | **82.6** | 44 | 5 | **89.8** | 0 | 1 | **0.0** | 2 | 13 | **13.3** |
| | AV | 1 | 21 | **4.5** | 42 | 22 | **65.6** | 6 | 6 | **50.0** | 0 | 6 | **0.0** |
| | DC | 20 | 4 | **83.3** | 37 | 40 | **48.1** | 5 | 5 | **50.0** | 1 | 13 | **7.1** |
| | DG | 41 | 1 | **97.6** | 33 | 12 | **73.3** | 6 | 0 | **100.0** | 3 | 7 | **30.0** |
| | EM | 43 | 9 | **82.7** | 137 | 66 | **67.5** | 36 | 8 | **81.8** | 25 | 3 | **89.3** |
| | GC | 79 | 0 | **100.0** | 23 | 21 | **52.3** | 8 | 1 | **88.9** | 9 | 2 | **81.8** |
| | MI | 3 | 1 | **75.0** | 129 | 2 | **98.5** | 2 | 2 | **50.0** | 12 | 8 | **60.0** |
| | OB | 11 | 10 | **52.4** | 14 | 13 | **51.9** | 4 | 2 | **66.7** | 16 | 5 | **76.2** |
| | PV | 61 | 2 | **96.8** | 10 | 13 | **43.5** | 0 | 2 | **0.0** | 4 | 4 | **50.0** |
| | SR | 21 | 1 | **95.5** | 12 | 12 | **50.0** | 7 | 2 | **77.8** | 9 | 6 | **60.0** |
| | **Total** | 418 | 54 | **88.6** | 486 | 212 | **69.6** | 76 | 30 | **71.7** | 173 | 67 | **72.1** |
| Mixed | AG | 19 | 20 | **48.7** | 23 | 12 | **65.7** | 3 | 6 | **33.3** | 3 | 2 | **60.0** |
| | CA | 5 | 12 | **29.4** | 6 | 11 | **35.3** | 2 | 3 | **40.0** | 2 | 5 | **28.6** |
| | MS | 10 | 18 | **35.7** | 2 | 12 | **14.3** | 1 | 0 | **100.0** | 0 | 1 | **0.0** |
| | PM | 5 | 9 | **35.7** | 20 | 16 | **55.6** | 7 | 8 | **46.7** | 5 | 1 | **83.3** |
| | **Total** | 39 | 59 | **39.8** | 51 | 51 | **50.0** | 13 | 17 | **43.3** | 10 | 9 | **52.6** |
| Phonologi-cal | AC | 6 | 9 | **40.0** | 15 | 8 | **65.2** | 2 | 8 | **20.0** | 0 | 4 | **0.0** |
| | DS | 8 | 11 | **42.1** | 13 | 11 | **54.2** | 1 | 0 | **100.0** | 13 | 6 | **68.4** |
| | GM | 1 | 3 | **25.0** | 8 | 12 | **40.0** | 4 | 14 | **22.2** | 0 | 1 | **0.0** |
| | LB | 7 | 9 | **43.8** | 2 | 4 | **33.3** | 2 | 0 | **100.0** | 1 | 1 | **50.0** |
| | MC | 22 | 37 | **37.3** | 53 | 65 | **44.9** | 11 | 12 | **47.8** | 10 | 15 | **40.0** |
| | MP | 1 | 6 | **14.3** | 10 | 9 | **52.6** | 0 | 2 | **0.0** | 1 | 1 | **50.0** |
| | RM | 16 | 30 | **34.8** | 4 | 4 | **50.0** | 1 | 0 | **100.0** | 3 | 1 | **75.0** |
| | TC | 4 | 5 | **44.4** | 6 | 8 | **42.9** | 3 | 2 | **60.0** | 1 | 4 | **20.0** |
| | VS | 2 | 6 | **25.0** | 13 | 16 | **44.8** | 0 | 3 | **0.0** | 1 | 7 | **12.5** |
| | **Total** | 67 | 116 | **36.6** | 124 | 137 | **47.5** | 24 | 41 | **36.9** | 30 | 40 | **42.9** |
| | $G^2$ | | | 15.71 | | | 4.39 | | | 5.64 | | | 0.86 |
| | p | | | **< .001** | | | **.04** | | | **.02** | | | .35 |

## Appendix D

see Table D1.

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