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Convergences and divergences between Neurolinguistic and Psycholinguistic data in the study of phonological and phonetic encoding: a parallel investigation of syllable frequency effects in brain-damaged and healthy speakers.

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Running head: syllable frequency in neurolinguistic and psycholinguistic data

Abstract

Theories of speech production suggest that phonetic encoding involves an access to stored syllable-sized articulatory plans. Both neurolinguistic and psycholinguistic investigations have reported an effect of the frequency of use of syllabic units, respectively on accuracy and errors in brain-damaged speakers and on production latencies in non-brain-damaged speakers. Beyond these convergent results, the fact that the same effects have been reported with brain-damaged patients with and without impairment ascribed at the level of phonetic encoding challenges the architecture of speech production models and the interpretation of patients' behavior. Here we carry out a fully parallel neurolinguistic and psycholinguistic investigation to address whether previous diverging results can be accounted for by methodological differences between neurolinguistic and psycholinguistic studies. We analyzed production accuracy in 14 brain-damaged speakers and production latencies in 24 non-brain-damages speakers using the same pseudo-word stimuli, same reading and repetition tasks and same multiple regression approach. Results replicate evidence from previous neurolinguistic and psycholinguistic studies on an influence of syllable frequency independently of other sublexical variables in both populations. In addition, the effect of syllable frequency on production accuracy was not limited to brain-damaged patients with impaired phonetic encoding. We suggest that these results are best accounted for by postulating interaction between phonological and phonetic encoding.

Keywords: phonological encoding, phonetic encoding, aphasia, syllable frequency

Introduction

Producing the sequences of speech-sounds that make-up a sentence involves encoding an abstract concept into an articulatory plan. Models of speech production postulate that, once a word has been selected, an abstract phonological make-up is planned before a more specified phonetic plan is encoded (Levelt, 1989; Levelt, Roelofs, & Meyer, 1999; Roelofs, 1997a). Phonological encoding involves the retrieval of the segmental and suprasegmental format of a selected word. Then, the retrieved abstract phonological information undergoes phonetic encoding processes, that is, the encoding of an articulatory plan that will be used as motor commands.

Most theories of speech production also suggest independent organization of phonological and phonetic encoding processes. Evidence in favor of this view is that each of these processes is affected by specific linguistic variables. Indeed, speed and accuracy of the retrieval of lexical-phonological representations are influenced by a number of linguistic factors such as lexical frequency (Alario, Ferrand, Laganaro, New, Frauenfelder, & Segui, 2004; Barry, Morrison, & Ellis, 1997; Jescheniak & Levelt, 1994; Oldfield & Wingfield, 1965) and phonological neighborhood density (Vitevitch, 1997, 2002); by contrast, phonetic encoding is thought to address syllable-sized phonetic plans and to be affected by the frequency of use of these syllabic representations (Levelt & Wheeldon, 1994). The effect of these variables on the encoding of the word forms have been long established and are supported by converging results from psycholinguistic experiments and from neurolinguistic data. To date, effects of phonological neighborhood have been reported on production latencies in healthy (non-brain damaged, NBD) speakers (Baus, Costa, & Carreiras, 2008; Vitevitch, 2002; Vitevitch & Sommers., 2003) and on production accuracy in brain-damaged (BD, aphasic) speakers (Goldrick, Folk and Rapp, 2010; Gordon, 2002; Kitteridge et al. 2008). The frequency of use of syllabic plans also affected production latencies in NBD speakers (Carreiras & Perea, 2004; Cholin & Levelt, 2009; Cholin, Dell, & Levelt, 2011; Cholin, Schiller, & Levelt,, 2006; Laganaro & Alario, 2006; Levelt & Wheeldon, 1994) and accuracy in BD patients (Aichert & Ziegler; 2004; Staiger & Ziegler, 2008; Laganaro, 2008).

Beyond these convergent results, there is at least one point on which psycholinguistic and neurolinguistic data diverge: the processing level at which stored syllabic representations are ascribed in models of speech production does not always fit with the underlying impairments in some reports of BD speakers whose production errors are affected by syllable frequency. In particular, psycholinguistic studies on the role of syllables in speech production clearly point to stored phonetic syllables and to a role of syllable frequency at the level of phonetic encoding (Cholin & Levelt, 2009; Laganaro & Alario, 2006). By contrast, the results from studies with brain-damaged speakers are less clear-cut, as reports of syllable frequency effects on production accuracy are not limited to patients whose impairment is attributed to phonetic encoding (Stenneken, Hofmann, & Jacobs, 2005; Laganaro, 2005). In particular, the following observation challenges the theoretical interpretation of the locus of stored syllabic units and the independence of phonological and phonetic encoding processes: that is, BD speakers with underlying impairment supposed at other processing levels than those which should be affected by syllable frequency also display an effect of this variable on production accuracy. However, these divergences may stem from different stimuli, different tasks or different languages across neurolinguistic and psycholinguistic studies. The purpose of the present study then is to clarify convergences and divergences between neurolinguistic and psycholinguistic data, by carrying out a parallel investigation with brain-damaged and NBD speakers. In the following, we will first review the literature on phonetic encoding in the psycholinguistic and neurolinguistic domains, focusing on syllable frequency effects. We will then elucidate on which points psycholinguistic data and neurolinguistic results seem to diverge.

Syllable-sized representations

Although some models of speech production have postulated stored abstract (phonological) syllabic units (e.g., Dell, 1986), the hypothesis of phonological syllable-sized representations was abandoned for a series of theoretical and experimental reasons. Only syllable-sized phonetic representations (motor plans) are postulated in most models. A primary motivation for this theoretical choice stems from the observation of sandhi phenomena in connected speech production (Levelt, 1989; Roelofs, 1997b). It is argued that resyllabification across word boundaries (eg. in a sequence like *cher ami* -“dear friend”-, the syllabic structure of the surface form [ΣE.{α.μι] - CV.CV.CV][1] - is different from that of the individual forms [ΣE{] – CVC - plus [αμι] - V.CV) requires that syllables are created on-line, based on phonological rules and cannot be stored at the phonological level. Experimental

[1] Dots mark syllable boundaries.

arguments against the representation of phonological syllables stem from psycholinguistic priming paradigms. Converging results from studies carried out in a variety of languages showed that syllables cannot be primed with phonological priming paradigms (Perret, Bonin, & Méot, 2006; Schiller, 1998; Schiller & Costa, 2006, but see Ferrand, Segui & Grainger, 1996; Ferrand, Grainger & Humphreys, 1997).

By contrast, other studies reported evidence for stored syllabic units with different paradigms. Syllabic priming effects have been reported with a form-preparation (implicit priming) paradigm (Cholin, Schiller & Levelt, 2004), in which subjects overtly produced the primes. It has also been shown that the frequency of the syllables composing the stimuli, i.e., the frequency of occurrence of syllable-sized units, affects production latencies. In those studies a facilitatory effect of high frequency syllables was reported with a variety of tasks and stimuli (*word and pseudo-word reading*: Carreiras & Perea, 2004; Laganaro & Alario, 2006; Perea & Carreiras, 1998; *learned word-symbol associations*: Cholin, Dell, & Levelt, 2011; Cholin, Levelt, & Schiller, 2006; Levelt & Wheeldon, 1994; *picture naming*: Laganaro & Alario, 2006). Although these results strongly support the notion of stored syllables, they do not represent indisputable evidence for a phonetic locus. Laganaro and Alario (2006) reported more direct empirical evidence for a phonetic locus of the syllable frequency effect. In this study, syllable frequency affected the production latencies in immediate production and in delayed production when an interfering task (articultory suppression) filled the delay, but not in a standard delayed production task. As the articulatory suppression task is thought to interfere with phonetic encoding processing while leaving phonological encoding relatively intact, these results point to a phonetic locus of the effect. In this view, the "syllabary" (Crompton, 1982) is a store containing a chunk representation for each syllable of the language, specifying its articulatory plan.

Syllable frequency effects in brain-damaged speakers

Some neurolinguistic studies also provide converging evidence for an effect of the frequency of use of syllabic units on production accuracy in brain-damaged speakers with impaired phonetic encoding (Aichert & Ziegler; 2004; Staiger & Ziegler, 2008). In these studies speakers with apraxia of speech (AoS) produced more errors on words or pseudo-words composed of low (vs. high) frequency syllables. The underlying impairment responsible for AoS is currently attributed to speech planning (Darley, Aronson and Brown, 1975), corresponding to an impairment at the level of phonetic encoding processes in psycholinguistic models of speech production (Code, 1998; Varley & Whiteside, 2001; Ziegler, 2008, 2009). Nevertheless, an effect of syllable frequency on speech errors produced by brain-damaged speakers was not limited to patients with AoS. Some studies have reported syllable frequency effects with BD patients presenting with impaired phonological encoding. Actually, syllable frequency effects were also reported on accuracy and on the substitution errors of patients with conduction aphasia (Laganaro, 2005; 2008; Laganaro & Zimmermann, 2010) and in the distribution of a jargon-aphasic's neologisms (Stenneken et al., 2005). These patients do not display the characteristics of apraxia of speech, their underlying impairment being attributed to phonological encoding processes as opposed to phonetic impairment (Blumstein, Cooper, Goodglass, Statlender, & Gottlieb, 1980; Lecours & Lhermitte, 1969; Nespoulous, Joanette, Ska, Caplan, & Lecours, 1987). Production accuracy in these patients is generally affected by lexical and/or phonological factors (Olson, Romani, & Halloran, 2007; Schwartz, Wilshire, Gagnon, & Polansky, 2004; Wilshire, 2002); therefore, observing an influence of the frequency of use of syllabic units in these patients challenges the phonetic interpretation of the locus of stored syllables on the basis of syllable frequency effects.

In sum, psycholinguistic and neurolinguistic studies seem to converge on the effect of syllable frequency in speech production, but they do not completely converge in relation to the phonetic locus of this effect. In particular, observing syllable frequency effects in patients with impaired phonological encoding challenges an interpretation of storage and retrieval of syllables limited to the level of phonetic encoding. However, before one can draw any theoretical conclusion from these observations, a methodological point should be clarified. Indeed, insufficient control of materials in the experimental paradigms or different languages and stimuli across psycholinguistic and neurolinguistic studies may account for these divergences. In the present study we carry out a parallel neurolinguistic and psycholinguistic investigation using the same stimuli and tasks with BD and NBD speakers to examine (i) whether the frequency of use of syllabic units influences production accuracy (in brain-damaged speakers) and production latencies (in non brain damaged speakers) independently of other factors, and (ii) whether syllable frequency effects on production errors are limited to patients with impaired phonetic encoding. First we investigate syllable frequency effects on reading and repetition errors in a group of 14 BD speakers. Then, we seek convergences with psycholinguistic data and analyze whether production latencies in NBD speakers are affected by the same variables as errors in BD speakers.

1. **Neurolinguistic study**

Here we investigate syllable frequency effects on production accuracy in BD speakers presenting with impaired phonological and/or phonetic encoding processes. Pseudo-word reading and repetition were used to elicit production as both tasks have been previously employed in studies analyzing infra-lexical predictors of production accuracy in BD speakers (Aichert & Ziegler, 2004; Laganaro, 2008; Romani & Galluzzi, 2005; Romani, Galluzzi, Bureca, & Olson, 2011; Zielger, Thelen, Staiger, & Liepold, 2008; Ziegler, 2009). Bisyllabic pseudo-words were selected, because they allow to manipulate sub-lexical variables minimizing the influence of other lexical factors. Given the difficulty of controlling all possible confound factors of syllable frequency with a factorial design, a multiple regression approach is more adequate.

Method

Material

The experimental stimuli were 160 bisyllabic pseudo-words. We selected 160 syllables covering a large frequency space (from 1 to 6160 occurrences per million words) in the French database LEXIQUE2 (New, Pallier, Brysbeart, & Ferrand, 2004). 80 syllables had a CV structure (occurrences from 10 to 5998 per million words), 40 were CVC (occurrences from 2 to 6160) and 40 CCV (occurrences from 1 to 4339). In addition, we selected 10 other CV syllables (“pivot syllables” hereafter) among French syllables with the highest frequency of use (above 6000 occurrences per million words) and created bisyllabic pseudo-words by associating each of the 160 syllables to a ”pivot syllable”. The 160 pseudo-words had the following syllabic structures: CVC.CV, CV.CVC, CCV.CV, CV.CCV (20 each) and CV.CV (80). For the reading task a standard orthographic transcription was used (ex. “guédé” for [gede], “traco” for [tRako]), following the more frequent French orthographic transcription for each phoneme[2].

[2] Although French has many monosyllabic words, it should be noted that only 31 percent of the selected

The mean syllable frequency was computed for each pseudo-word. In addition to this variable of interest, the following properties were computed for all pseudo-words from the French database LEXIQUE2 (New et al., 2004): mean phoneme frequency, mean biphone frequency, number of phonological neighbors, number of orthographic neighbors and length (see Appendix 1). As several factors measure the occurrence of infra-lexical units, they are bound to be correlated (collinearity kappa =283.62, calculated following Belsley, Kuh, & Welsch, 1980, Baayen, et al., 2008). In order to reduce collinearity, we visualized the collinearity structure with hierarchical clustering (see Appendix 1) following the procedure described by Baayen (2008, p. 198-201). Then, we decorrelated the factors within each cluster by residualizing them, as suggested by Jaeger (2010). Collinearity with the orthogonalized variables drop to kappa= 3.94, while the correlation between each residualized variable and its original values was above $r > .822$.

Participants

The participants were 14 native French-speaking patients with a clinical diagnosis of aphasia or apraxia of speech following a single left hemisphere stroke (mean age: 48.8, range: 28-73; 4 women). The inclusion criteria for the patients were as follows: production of phonological and/or phonetic errors in all speech production tasks (spontaneous speech, reading and repetition), normal or mildly impaired speech comprehension (assessed with oral and written comprehension tasks from the MT-86, Nespoulous et al., 1992), mild anomia and no semantic or lexical-semantic impairment (unimpaired or limit scores at the picture and word sub-tests of the Pyramid and Palms test, Howard & Patterson, 1992). In addition, only patients producing at least 5% of errors in the experimental tasks were retained and patients without a clear diagnosis of apraxia of speech (AoS) or of conduction aphasia (CA) were excluded.

Seven patients (AoS1 to AoS7 in Appendix II) had a clear diagnosis of apraxia of speech, which was based on clinical record and verified through the analysis of their speech samples (from the experimental tasks and from an additional sentence repetition task). This was based on the following standard criteria currently used for the diagnosis of AoS (McNeil,

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syllables corresponded to monosyllabic phonological and orthographic words, 36% were non-words and 33% were pseudo-homophones (the correlation between the total frequency of use of the selected syllables and their frequency as monosyllabic words is $r=.233$).

Pratt, & Fossett 2004; Romani & Galluzzi, 2005; Ziegler, 2009): effortful speech, more than 5% of phonetic distortions and presence of schwa insertion in consonant clusters. Three patients also had Broca aphasia (AoS3, AoS6 and AoS7). Seven patients (CA1 to CA7) had a diagnosis of conduction aphasia: they had fluent speech and produced mainly perceptually well formed phonemic errors.

Procedure

Subjects were asked to read aloud and to repeat each pseudo-word during two or more separate sessions.

a.Reading. For the reading task, pseudo-words were presented on a paper sheet and the subjects had to read them aloud without time pressure.

b.Repetition. For the repetition task the experimenter pronounced each pseudo-word and repeated it if necessary. The participants were asked to repeat the pseudo-word as accurately as possible.

Analyses

The whole sessions were recorded and digitized. A double scoring procedure was used: the experimenter scored and transcribed the productions “on-line” and a second person transcribed the productions from the recording. Only productions that were correct at first production attempt were scored as correct. Phonemically well-formed errors (phoneme substitution, omission or epenthesis) as well as no-responses and fragments were scored as production errors. Productions containing only phonetic distortions (i.e. phonemically not well-formed but perceptually identifiable phonemes) were considered to be correct productions, but were coded separately as *phonetic* errors.

Accuracy data was fitted with a generalized linear mixed-effects model for binomially distributed outcomes (Jaeger, 2008), with the R-software (version 2.11.1). For the fixed-part of the model, we sought the regression model which best fitted with the data with the least possible predictors. The entire set of orthogonalized predictors was entered at first step. Then, the non-significant factors were removed following a stepwise procedure. Participants, items and CV-structure were included as random-effects factors with adjustments on slope and on intercept for each factor. Likelihood ratio tests were used to choose the most appropriate model (see Pinheiro & Bates, 2000 for more information on this procedure). Models with the most complex random effects structure (with by-participant and by-item adjustments on both slopes and intercept) never provided a significantly better fit than models with only intercept adjustments.

Somers'D was used to calculate the correlation between the predicted and the observed accuracy.

The analyses were carried out on accuracy on the entire patient's group and on each diagnostic subgroup (AoS and CA).

Results

a. Reading

Two patients (one from the AoS subgroup and one from the CA subgroup) could not undergo the whole reading task, either because of particular difficulty with pseudo-word reading or because of interrupted sessions, and their reading data were excluded from the analysis. Mean pseudo-word production accuracy for the entire group was 73% (12 patients, SD: 14, range 44%-90%). Most errors (71%) were single segment errors, either phoneme substitution (52%) or omission or addition (19%); the remaining errors were coded as "complex" errors (errors involving more than one phoneme) or as incomplete (fragmental) productions (see Appendix II). The summary of the significant fixed-effect variables in the fitted model for reading accuracy is displayed in Table 1.

[Table 1]

Syllable frequency, phonological neighborhood and orthographic neighborhood were significant predictors of reading accuracy on the whole group and on both subgroups (except for orthographic neighborhood in the CA subgroup). None of the other sub-lexical frequency counts reached significance in the regression model. Because residualized variables were entered in the model, the exact interpretation of the estimate coefficients is not possible, but we can observe that all predictors facilitate the correct production.

b. Repetition

Mean pseudo-word production accuracy for the entire group was 77% (14 patients, sd: 11, range 53-94%). Most errors (84%) were single phoneme errors, either phoneme substitution (64%) or omission/addition (18%); the remaining errors were "complex" errors involving more than one phoneme or fragmental productions (see Appendix II).

[Table 2]

Syllable frequency facilitated repetition accuracy in both subgroups (see Table 2). In addition, length in phonemes and other sub-lexical frequency counts (phoneme and biphone frequency) influenced accuracy only in the AoS subgroup.

c. Phonetic errors analysis

In the analyses presented above, syllable frequency affected reading and repetition accuracy in both diagnostic subgroups. As described in the method section, isolated *phonetic* distortions were not scored as errors: only phonemic errors (phonemically identifiable productions) were scored as incorrect production. However, *phonetic* errors also co-occurred sometimes with phonemic errors. To tease apart the influence of syllable frequency on phonemic errors and on phonetic transformations, we run an additional analysis on the rate of *phonetic* errors, including those observed in isolation and those associated to a phonemic error (57% of the phonetic errors were associated to another error in the reading data and 62% in the repetition data). The same procedure as the one described for production accuracy was applied to phonetic errors. Results are presented in Table 3.

[Table 3]

In both production tasks, several sub-lexical frequency counts (phoneme, biphone, and syllable) predicted the production of *phonetic* errors, with more errors on less frequent units. Length in phonemes also predicted this kind of errors, with more errors on longer words. In the repetition task an opposite effect of phonological neighborhood also appeared (more phonetic errors on pseudo-words with many phonologically similar words).

Discussion

The results on the group of BD speakers showed significant facilitatory effects of syllable frequency on production accuracy in both tasks, namely reading aloud and repetition. Pseudo-words composed of high frequency syllables were less error-prone than pseudo-words composed of lower frequency syllables. These results were consistent with reports from previous studies using factorial approaches with BD speakers (Aichert & Ziegler; 2004;

Laganaro, 2008). In addition, the multiple regression approach used in the present study clearly showed that the frequency of use of syllabic units influences production accuracy in BD speakers independently of other sub-lexical frequency counts: the observed effect cannot be attributed to collinearity with other factors, as orthogonalized predictors were entered in the analysis.

Crucially for our purpose, the syllable frequency effect was not limited to patients with impaired phonetic encoding (with AoS): overall accuracy was predicted by syllable frequency in both subgroups. However, other sub-lexical frequency counts (phoneme and biphone frequency) added a significant contribution to the model only in the AoS subgroup: phoneme and biphone frequency influenced production accuracy in the repetition task in the AoS subgroup and they predicted *phonetic* errors (which characterize the production of patients with AoS) in both tasks. Thus, it appears that syllable frequency alone predicted the production of phonemic errors while several sub-lexical units also contribute to the production of phonetic transformations.

Before any further discussion of these results, we first verify whether the same factors affecting production accuracy in BD speakers also influence reading and repetition latencies in NBD speakers.

2. Psycholinguistic study (NBD speakers)

Here we seek syllable frequency effects on production latencies in NBD speakers on the same material and tasks used with BD speakers (Study 1). To completely parallel the neurolinguistic study, besides a pseudo-word reading task, for which syllable frequency effects on production latencies have been repeatedly reported (Carreiras & Perea, 2004; Laganaro & Alario, 2006; Perea & Carreiras, 1998), we also run a pseudo-word repetition task, although repetition tasks are unusual in psycholinguistic investigations on speech production.

Method

Material

The experimental stimuli were the same 160 pseudo-words used in the Neurolinguistic study.

Participants

Two different groups of 24 native French-speaking undergraduate students participated in the reading and the repetition task. They received course credits for their participation.

Procedure

Participants were tested individually in a quiet room. They sat in front of the computer screen and wore a head-mounted microphone. In each experimental trial a "+" sign appeared in the middle of the screen for 500 milliseconds, immediately followed by a pseudo-word (either written or auditory presentation). Participants were asked to read or repeat (see below) each stimulus as fast and as accurately as possible. The experiment was controlled by the software DmDx (Forster & Forster, 2003). Production latencies (RTs) were measured with the DmDx vocal key. All responses were digitized and recorded: production accuracy and vocal key were checked with CheckVocal (Protopapas, 2007).

a .Reading task: Items were printed in lowercase 24-point Courier New font in reverse video mode (white lines on black screen) and remained on the screen until the voice key was triggered.

b. Repetition task. The pseudo-words were read and digitized by a female voice with a neutral intonation. Each pseudo-word was placed in a single sound file lasting 800 ms, aligned to the end of the waveform (mean pseudo-word duration: 581 ms, SD: 75.4 ms). The voice-key was triggered from the end of the pseudo-word.

Analyses

Reading and repetition latencies were systematically checked and corrected when necessary. RT data were fitted with a general linear mixed-effects model (Baayen, Davidson, & Bates, 2008) with the R-software (version 2.11.1). The same predictors as in the neurolinguistic study were entered at first step plus the following predictors: the properties of the first phoneme which can modulate the measure of production latencies (Kessel, Treiman, & Mullenix, 2002) were captured with two variables: a sonority scale from 1 for low sonority to 8 for high sonority (Clemens, 1990) and a six-category scale[3]; for the repetition task the

[3] The six categories were obstruent/fricative; obstruent/occlusive; sonorant/fricative; sonorant/liquid; sonorant/occlusive and sonorant/nasal.

duration of each auditory pseudo-word was also included (Lipinski & Gupta, 2005). Then, the non-significant predictors were removed following a stepwise procedure. R-squared between the fitted data and the real data were calculated as in Baayen and Milin (2010).

Participants, items and CV-structure were included as random-effect factors with slope and intercept adjustments for each factor. Likelihood ratio tests were used to choose the most appropriate model (see Pinheiro & Bates, 2000 for more information on this procedure). Models with the most complex random effects structure (with by-participant and by-item adjustments on both slopes and intercept) never provided a significantly better fit than models with only intercept adjustments.

Results

a. Reading

Trials with production errors or technical (voice-key) problems (4.01%) and outlier values (below 300 ms or above 1000 ms, 0.81%) were excluded from the analyses. Mean RT was 570 ms (SD=107 ms).

Syllable frequency, the sonority of the first phoneme[4], phonological and orthographic neighborhood and length in letters were significant predictors of reading RTs (see Table 4). RTs were faster for high frequency syllables, dense phonological/orthographic neighborhood and shorter stimuli. None of the other sub-lexical frequency measures (phoneme or biphone frequency) influenced reading aloud latencies.

[Table 4]

b. Repetition

[4] For both reading and repetition latencies, when both factors (sonority of the first phoneme and category of the first phoneme) were included in the model, only the first variable (sonority) was a significant predictor. When each factor was included separately, they were both significant but the model with the sonority of the first phoneme had a higher R-squared.

Trials with production errors or technical (voice-key) problems (5.10%) and outlier values (below 50 ms or above 800 ms, 2.13%) were excluded from the analysis. Mean RT was 339 ms (SD=125ms).

[Table 5]

Sonority of the first phoneme and pseudo-word duration were significant predictors of repetition latencies; syllable frequency also marginally predicted RTs. All factors were facilitatory, including pseudo-word duration (shorter latencies for longer pseudo-words).

Discussion

These results with NBD speakers confirm previous results on independent effects of syllable frequency on pseudo-word reading latencies reported in the literature (see the Introduction); in addition, a syllable frequency effect was also observed in the repetition task, although this effect was marginal.

Previous results from the literature (e.g., Cholin et al., 2006, 2009, 2011; Laganaro & Alario, 2006; Levelt & Wheeldon, 1994; Levelt et al., 1999) pointed to a phonetic locus of syllable frequency effects (phonetic encoding, see the Introduction). The observation that syllable frequency also influenced pseudo-word repetition seems to constitute a further argument in favor of a locus of syllable frequency effects on a process which is common to reading and repetition. However, we cannot exclude here that syllable frequency effects on RTs are also due to perception processes, in particular in the repetition task, which interpretation is less straightforward. Nevertheless, in studies using specific recognition tasks such as lexical decision, syllable frequency usually had an inverse (inhibitory) effect (Alvarez, Carreiras & Vega, 2000; Hutzler, Conrad & Jacobs, 2005; Mathey and Zagar, 2002; Perea & Carreiras, 1998), while syllable frequency had a facilitatory effect in the present results both on reading and repetition latencies.

In addition to our variable of interest, the sonority of the first phoneme affected RTs in both tasks. The effect of sonority is well known and is tied to the sensibility of the vocal key to different properties of the first phoneme (Kessel et al., 2002, see also Rastle et al., 2002). Phonological and orthographic neighborhood and number of letters also predicted production latencies in the reading task. These effects converge with those reported in the literature on reading (Ferrand et al., in press; Mulatti, Reynolds & Besner, 2006; New, Pallier, Brysbeart & Ferrand, 2006; Yates, Lockes, & Simson, 2004).

An in depth discussion of these factors goes beyond the purpose of the present study; the important issue here is that syllable frequency facilitated production latencies independently of other possible confound factors. Crucially for our purpose, these results converge with those from BD speakers: this point will be further discussed in the General discussion.

General discussion

Our main aims here were (1) to seek convergences and divergences between neurolinguistic and psycholinguistic data on syllable frequency effects when using the same stimuli and tasks with BD and NBD speakers and (2) to clarify whether effects of the frequency of use of syllabic units on production accuracy are consistent with an underlying phonetic impairment in BD speakers. Table 6 summarizes the main neurolinguistic and psycholinguistic results.

[Table 6]

A clear convergence of the effect of syllable frequency emerged across tasks and populations: production accuracy was higher and production latencies were shorter for pseudo-words composed of frequent syllables. In addition, in the two populations the facilitatory effects of phonological/orthographic neighbors were limited to the reading task and none of the other sub-lexical frequency counts influenced the data, except for the subgroup of AoS patients. Thus, results from NBD and BD speakers converge when the same stimuli, tasks and analyses are used: the frequency of use of syllabic units influences speed and accuracy of pseudo-word production independently of other possible confounds.

In addition, the present results are also partially congruent with previous sparse results from the neurolinguistic literature reporting an effect of the frequency of use of syllabic units in BD patients independently of the supposed underlying impairment (phonetic or phonological). Actually, the effect of syllable frequency on production accuracy was not limited to patients whose impairment was ascribed at the level of phonetic encoding (AoS subgroup). These results challenge the interpretation of the locus of syllable frequency effects and/or of patient classification in the framework of serial models of speech encoding, as only patients with impairment at the level of stored syllabic representations (phonetic encoding) are expected to produce more errors on low frequency syllables. The only difference observed across the two subgroups of BD speakers concerns the influence of OTHER sub-lexical probability counts. Effects of phoneme and biphone frequencies were observed exclusively in the data of patients with a diagnosis of AoS (on accuracy and on phonetic errors).

Processing level affected by syllable frequency

As exposed in the Introduction, most empirical evidence on stored syllabic units points to an effect of their frequency of use during the encoding of the phonetic plan, as suggested in Levelt et al.'s model of speech production (1999). The observation that the frequency of use of French syllables influenced reading and repetition in both populations further argues in favor of a locus of the effect on an encoding level common to both production tasks. Differently from syllable frequency, which facilitated both reading and repetition, phonological neighborhood only influenced reading latencies (in NBD speakers) and accuracy (in BD speakers). These results are in line with common theoretical accounts, suggesting that phonological neighbourhood and syllable frequency do not affect the same encoding levels (but see limitations in the interpretation of repetition RTs exposed in the previous discussion).

One crucial point here concerns the results of the two patient subgroups. The question is why syllable frequency affects production accuracy regardless of the underlying level of impairment; in other words, why does the frequency of use of syllables also affect production accuracy in patients who a priori do not have impaired retrieval or encoding of syllabic gestural scores. We may exclude an interpretation of syllable frequency effects in non-AoS patients accounted for by mechanisms other than speech production (e.g., visual input processes): although both reading and repetition tasks also involve input processes, a perception/recognition locus of the effect can be discarded for the following reasons: (1) an inverse (inhibitory) effect of syllable frequency has been reported with recognition tasks such

as lexical decision (Alvarez, Carreiras & Vega, 2000; Hutzler, Conrad & Jacobs, 2005; Mathey and Zagar, 2002; Perea & Carreiras, 1998, see previous Discussion), and (2) facilitatory effects of the frequency of syllabic units similar to those observed here have also been reported in tasks which do not involve perception such as picture naming (Laganaro & Alario, 2006) and in spontaneous speech (Staiger & Ziegler, 2008; Stenneken, et al., 2005).
In the following, we will discuss three possible explanations of the similarity of syllable frequency effects in the two diagnostic subgroups in the framework of speech production.

Phonological syllables. One explanation may be linked to the level of syllabic representations. The divergences relative to the level of impairment in BD speakers whose production accuracy is affected by syllable frequency may be solved by postulating that both phonological and phonetic syllabic representations are stored and retrieved during speech planning. Within this kind of framework, syllable frequency effects observed in non-AoS patients (CA patients, whose underlying impairment is attributed to phonological encoding) may arise from impaired access/encoding of stored phonological syllables. Although some speech production models hold that phonological syllables are stored in the lexicon (Dell, 1986), the above interpretation has been discarded in the psycholinguistic literature in the light of converging empirical evidence pointing to phonetic-only syllabic representations (Cholin, Dell & Levelt, 2011; Laganaro & Alario, 2006). Although the hypothesis of stored phonological syllables has not been completely abandoned (see Chen, Chen & Dell, 2002 and Farrell & Abrams, 2011, for interpretations in line with stored phonological syllables), the present research does not allow us establish a phonological locus of stored syllables.

Interaction between phonological and phonetic encoding. An alternative explanation is tied to the mechanisms underlying phonological and phonetic encoding. An interactive architecture of speech production may account for the present results, if the encoding of a phonological form is affected by the availability of phonetic representations. The retrieval of phonological codes may be facilitated via feedback from stored phonetic syllables, resulting in higher accuracy in producing pseudo-words composed of high frequency syllables in patients with impaired phonological encoding. The degree of interaction within the speech production system has been largely debated with regard to other processing levels, i.e., between lexical-semantic and lexical-phonological levels of encoding (Dell, 1985; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997; Levelt et al., 1991; Levelt et al., 1999; Rapp & Goldrick, 2000). Recently, interaction between phonological and phonetic levels of encoding has also been postulated in the light of empirical results with NBD speakers, showing that lexical-phonological properties (e.g., phonological neighborhood, lexical frequency) affect the phonetic properties of the produced sentences (Baese-Berk & Goldrick, 2009, McMillan, Corley & Lickley, 2009; McMillan & Corley, 2010). The influence of lexical-phonological properties on phonetic realization has been taken as an evidence for cascading activation from phonological to phonetic encoding (see Goldrick & Blumstein, 2006). Alternatively, an integrated account of phonological and phonetic representations has also been sketched to account for these results (Goldrick et al., 2011): in such proposals lexical representations are associated to more detailed phonetic representations rather than to merely abstract phonological codes. This proposal coupled with cascading activation allowed to interpret the contrasting results of lexical frequency effects on speech errors (more errors on less frequent words) on the one side, and enhanced phonetic properties in the production of low- frequency words (Bell, 2009) on the other side. In this account, low-frequency words are associated to lower phonetic variability than high-frequency words, giving rise to enhanced phonetic realization and to higher error rate. Regarding the effect of syllable frequency in pseudo-word production accuracy, cascading activation alone is not enough to account for an influence of stored phonetic syllables on the retrieval of phonological codes. On the other hand, if integrated phonological-phonetic representations are encoded for speech production, no differences are expected across patients' subgroups, which is also in accordance with the present results. However, a model blending phonological-phonetic representations should integrate the frequency of sub-lexical units to account for the present data. In particular, it is unclear how the frequency of use of syllabic units may play a role in case of stored phonological-phonetic variants rather than of abstract representations. In addition, in the light of integrated phonological-phonetic processes, the neurolinguistic diagnostic categories differentiating AoS from CA should also be questioned.

Patterns of impairment in BD speakers. Finally, we can account for the present results by assuming that most patterns of impairment in BD speakers are not pure. This means that without exhibiting clear patterns of AoS, most patients might have overlapping phonological and phonetic impairments. Postulating mixed impairments after brain damage is not novel.

Regarding other processing levels, it is largely acknowledged that most patients display mixed patterns rather than pure lexical-semantic or lexical-phonological impairment for instance (Foygel and Dell, 2000; Schwartz et al., 2006). Therefore, one might easily consider that mixed phonological-phonetic patterns are more frequent than pure (phonological or phonetic) patterns of impairment (see McNeil et al., 1990 for similar conclusions). According to this interpretation, patients from all clinical diagnostic categories should display some degree of impaired phonetic encoding, affecting the ease of producing low frequency syllables. It should be reminded here however, that one result clearly differentiated the two diagnostic subgroups: an influence of frequency counts of other sub-lexical units was observed only in the data of the AoS subgroup. Biphone frequency effects may capture consonant cluster effects, known to affect production accuracy in AoS patients (Romani & Galluzzi, 2005; Romani et al., 2011; Ziegler, 2009). Phoneme frequency effects have also been reported on phoneme substitution errors (Goldrick & Rapp, 2007; Laganaro & Zimmermann, 2009) and phoneme frequency effects have been interpreted as a confound of sonority in a patient with impairment attributed to articulatory planning (Romani et al., 2002). In the present study we excluded the possibility of phoneme and biphone frequency counts to be confounded with syllable frequency by careful orthogonalisation of these factors. However, regarding the influence of these two variables on phonetic errors, we may not be able to disentangle here whether they are real frequency effects of if they are capturing other phenomena (such as sonority and consonant clusters). Fact is that these results pointed to a real difference across the two clinical diagnostic categories elsewhere than in the influence of syllable frequency: as a consequence, if we assume mixed patterns of impairment, this should be interpreted as *partial overlap* across underlying patterns of impairment. In all cases, supposing mixed patterns of impairment is not independent of an assumption of interactivity in speech production. In fact, mixed patterns of impairments have largely fed the debate about the amount of interaction in models of speech production (Dell et al., 1997; Foygel & Dell, 2000; Rapp & Goldrick, 2000; Schwartz, Wilshire, Gagnon, & Polansky, 2004). Regarding speech errors produced by NBD speakers, a continuum between phonemic errors and phonetic transformations has been proposed by McMillan and Corley (2010). The authors suggested that cascading and feed-back activation between lexical and phonological representations leads to the simultaneous activation of target and non-target phonemes (triggered by competing lexical activation), leading either to articulatory variations (phonetic transformations) or to whole phoneme substitution errors.

Thus, these two possible explanations (interaction between phonological and phonetic encoding and mixed patterns of impairment) of the incongruent results of syllable frequency effects in BD speakers are interconnected and need to be further investigated jointly.

In conclusion, neurolinguistic and psycholinguistic data clearly converge indicating that the frequency of use of syllables facilitates speed and accuracy of pseudo-word production in both reading and repetition. By contrast, the present study also confirms that syllable frequency affects error rate in brain-damaged speakers whose supposed pattern of impairment is ascribed at different levels of processing. These divergences challenge both, the architecture of speech production models and the interpretation of patients' behavior, as they can be interpreted as the result of interaction between phonological and phonetic encoding or as the indication that even patients without standard symptoms of AoS may have impaired access to stored phonetic syllabic plans. Future research, should take advantage of careful comparison of psycholinguistic and neurolinguistic data, as this integration can lead to reconsider both psycholinguistic models and the interpretation of patient behavior.

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TABLES

Table 1

Table 1. Summary of the fixed effects in the generalized linear mixed model fitted for reading accuracy for the entire patient group data and for subgroups of patients with apraxia of speech (AoS) and patients with conduction aphasia (CA).

	All patients (N=1920, Somers D=.491)				AoS (N=960, Somers D=.438)				CA (N=960, Somers D=.580)			
	Coeff.	SE	z	P	Coeff.	SE	z	P	Coeff.	SE	z	P
SylF	0.41	0.141	2.91	<.01	0.43	0.179	2.40	<.02	0.45	0.206	2.18	<.05
PhNeig	0.82	0.250	3.27	<.01	0.81	0.307	2.65	<.01	0.49	0.291	1.70	= .08
OrNeigh	0.75	0.267	2.82	<.01	0.91	0.336	2.71	<.01				

SylF: syllable frequency (log); PhNeigh: phonological neighborhood (log); OrNeig: orthographic neighborhood (log).

Table 2

Table 2.

Summary of the fixed effects in the generalized linear mixed models fitted for repetition accuracy for the entire patient group data and for subgroups of patients with apraxia of speech (AoS) and patients with conduction aphasia (CA).

	All patients (N=2240, Somers D=.495)				AoS (N=1120, Somers D=.388)				CA (N=1120, Somers D=.653)			
	Coeff.	SE	z	P	Coeff.	SE	z	P	Coeff.	SE	z	P
SylF	0.66	0.133	4.94	<.0001	0.81	0.172	4.71	<.0001	0.63	0.226	2.81	<.01
PhonF					3.00	1.337	2.25	<.05				
BiphF					1.63	0.788	2.07	<.05				
NbPhon					-1.03	0.219	-4.73	<.0001				

SylF: syllable frequency (log); PhonF: phoneme frequency (log); BiphF: biphone frequency (log); NbPhon: length in phonemes.

Table 3

Table 3.

Summary of the fixed effects in the generalized linear mixed models fitted for *phonetic errors* in reading and repetition for the entire patient group data.

	Reading (Somers D =.674)				Repetition (Somers D=.692)			
	Coeff.	SE	z	P	Coeff.	SE	z	P
SylF	-0.43	0.25	-1.73	=.08	-0.67	0.252	-2.65	<.01
PhNeig					0.84	0.404	2.08	<.05
PhonF	-4.04	2.009	-2.01	<.05	-8.03	2.242	-3.58	<.001
BiphF	-2.32	1.145	-2.02	<.05	-4.74	1.220	-3.89	<.001
NbPhon	0.88	0.336	2.62	<.01	1.54	0.381	4.03	<.0001

SylF: syllable frequency (log); PhNeig: Phonological Neighbourhood (log); PhonF: phoneme frequency (log); BiphF: biphone frequency (log); NbPhon: length in phonemes.

Table 4

Table 4. Results of mixed effects regression model fitted for reading latencies

	RT (R^2=.473)			
	Coeff.	SE	T	P
Sonor	-0.01	6E-04	-7.74	<.0000
SylF	-0.01	0.004	-3.16	<.01
PhNeig	-0.03	0.006	-4.84	<.0001
OrNeig	-0.02	0.007	-2.89	<.01
NbLett	0.01	0.002	4.35	<.0001

Sonor: sonority of the first phoneme; SylF: syllable frequency (log); PhNeigh: phonological neighborhood (log); OrNeigh: orthographic neighborhood (log); NbLett: length in letters.

Table 5. Results of mixed-effects regression model fitted for repetition latencies.

	RT (R^2=.562)			
	Coeff.	SE	T	P
Sonor	-0.007	0.001	-5.688	<*.0001*
SylF	-0.007	0.004	-1.890	=.058
PW duration	-0.107	0.026	-4.047	*<.001*

Sonor: sonority of the first phoneme; SylF: syllable frequency (log); PW: pseudo-word.

Table 6

Table 6: Summary of main effects in the neurolinguistic (BD speakers) and the psycholinguistic (NBD speakers) data

	Reading				*Repetition*			
	BD			NBD	BD			NBD
	AoS (accuracy)	CA	Phonetic errors	(RT)	AoS (accuracy)	CA	Phonetic errors	(RT)
Syllable frequency effect	YES	YES	YES*	YES	YES	YES	YES	YES*
Neighborhood effect	YES	YES	-	YES	-	-	YES	-
Other sub-lexical frequencies	-	-	YES	-	YES	-	YES	-

*marginal