

Research Article

Do Patients With Neurogenic Speech Sound Impairments Benefit From Auditory Priming With a Regular Metrical Pattern?

Ingrid Aichert,^a Katharina Lehner,^a Simone Falk,^{b,c} Mona Späth,^a and Wolfram Ziegler^a

AQ1 Purpose: Earlier investigations based on word and sentence repetition tasks had revealed that the most prevalent metrical pattern in German (the trochee)—unlike the iambic pattern—facilitates articulation in patients with apraxia of speech (AOS; e.g., Aichert, Späth, & Ziegler, 2016), confirming that segmental and prosodic aspects of speech production interact. In this study, we investigated if articulation in apraxic speakers also benefits from auditory priming by speech with a regular rhythm. Furthermore, we asked if the advantage of regular speech rhythm, if present, is confined to impairments at the motor planning stage of speech production (i.e., AOS) or if it also applies to phonological encoding impairments.

Method: Twelve patients with AOS, 12 aphasic patients with postlexical phonological impairment (PI), and 36 neurologically healthy speakers were examined. A sequential synchronization paradigm based on a sentence completion task was

conducted in conditions where we independently varied the metrical regularity of the prime sentence (regular vs. irregular prime sentence) and the metrical regularity of the target word (trochaic vs. iambic).

Results: Our data confirmed the facilitating effect of regular (trochaic) word stress on speech accuracy in patients with AOS (target effect). This effect could, for the first time, also be demonstrated in individuals with PI. Moreover, the study also revealed an influence of the metrical regularity of speech input in both patient groups (prime effect).

Conclusions: Patients with AOS and patients with PI exploited rhythmic cues in the speech of a model speaker for the initiation and the segmental realization of words. There seems to be a robust metrical influence on speech at both the phonological and the phonetic planning stages of speech production.

*“Hat/der/al/te/He/xen/meis/ter/
sich/doch/ein/mal/weg/be/ge/ben...”*

“Gone’s for once the old magician...”
(Goethe)

These are the first two lines of the famous verses from Goethe’s “Sorcerer’s Apprentice.” A prominent feature of the lyrical text excerpt is its underlying speech rhythm: Stressed (printed in bold in the example)

and unstressed syllables are alternating regularly, resulting in a consistent trochaic metrical pattern. The trochaic pattern, that is, a stressed syllable followed by an unstressed syllable, is assumed to be the most frequent, unmarked foot pattern in many languages, such as German or English (Domahs, Wiese, Bornkessel-Schlesewsky, & Schlewsky, 2008; Hayes, 1995). In German, for example, the disyllabic trochee is the most common phonological word (e.g., *Nase*, English: nose), with 41% of monomorphemic German words comprising two-syllable trochees (Féry, 1998). Therefore, Goethe’s poetic meter strictly obeys the preference of a trochaic pattern of German.

The rhythmical nature of speaking seems to play an important role in different speech processing domains. On the one hand, metrical stress is known to have an impact on auditory speech processing (e.g., Rothermich, Schmidt-Kassow, & Kotz, 2012). On the other hand, the prosodic properties of words and sentences are also assumed to have a strong influence on both phonological and phonetic mechanisms in speech production. For example, access to the phonological form of a word during speech production involves the encoding of segmental and metrical information,

AQ2 ^aClinical Neuropsychology Research Group (EKN), Institute of Phonetics and Speech Processing, Ludwig Maximilian University of Munich, Germany

^bLaboratoire Phonétique et Phonologie, Université Sorbonne Nouvelle Paris, France

^cInstitute of German Philology, Ludwig Maximilian University of Munich, Germany

Correspondence to Ingrid Aichert: ingrid.aichert@ekn-muenchen.de

Editor-in-Chief: Ben Maassen

Received May 3, 2018

Revision received October 30, 2018

Accepted February 10, 2019

https://doi.org/10.1044/2019_JSLHR-S-CSMC7-18-0172

Publisher Note: This article is part of the Special Issue: 2017

International Conference on Speech Motor Control: Speech Motor Control in Normal and Disordered Speech.

Disclosure: The authors have declared that no competing interests existed at the time of publication.

which are often viewed as two separate processes (e.g., Levelt, Roelofs, & Meyer, 1999). In Levelt's model, the metrical frame of an intended word specifies the number of syllables and, in cases of irregular stress, the main stress position. For items with regular stress, that is, when stress assignment is predictable, the metrical structure is generated by default (Roelofs & Meyer, 1998). Studies of neurologically healthy speakers also pointed at a close link between segmental and metrical aspects at the phonological and the phonetic encoding levels. There is evidence, for instance, that the occurrence of slips of the tongue is modulated by prosodic prominence. In a tongue twister experiment (Croot, Au, & Harper, 2010), it was shown that sentence-level accent protects against errors. Furthermore, lexical stress influences word reading latency and accuracy (Sulpizio, Spinelli, & Burani, 2015), and predictable metrical structure reduces phonological sequencing errors and hesitations during the reproduction of nonsense word sequences (Tilsen, 2011). The "Prosody First" model proposed by Keating (2006) provides a comprehensive theoretical framework for such interactions.

With regard to data from neurological patients, there is only scant evidence of prosodic influences on speech production so far. In aphasic phonological impairment (PI), the metrical form of words is considered to be much less vulnerable to error than their segmental structure. Earlier reports of metrical disturbances have primarily been confined to dyslexic patients (e.g., Black & Byng, 1986; Marshall & Newcombe, 1973; Miceli & Caramazza, 1993), but several case reports have meanwhile documented patterns of metrical errors in naming, repetition, or reading, also in aphasic patients (Aichert & Ziegler, 2004a; Cappa, Nespor, Ielasi, & Miozzo, 1997; de Bree, Janse, & van de Zande, 2007; Howard & Smith, 2002; Laganaro, Vacheresse, & Frauenfelder, 2002). In some of the reported cases, a preponderance of phoneme errors was observed on unstressed as compared to stressed syllables (Nickels & Howard, 1999). Other patients misstressed words with an irregular metrical pattern (Cappa et al., 1997; Laganaro et al., 2002). Aichert and Ziegler (2004a) reported on a patient with largely preserved segmental encoding processes, but with a tendency to produce the unmarked metrical pattern of German, that is, two-syllabic trochaic words.

Some authors proposed that the problems with word stress in patients with PI represent a lexical-level problem of accessing the irregular metrical patterns stored with the lexical items (Butterworth, 1992; Cappa et al., 1997; Laganaro et al., 2002). As a consequence, the patients are forced to generate the unmarked phonological structure. Howard and Smith (2002) accounted for such problems by assuming that the parallel computation of segmental and metrical word form information is particularly resource consuming. Limitations of processing resources may therefore lead to problems in spelling out the metrical frame of words with unpredictable stress (for a limited verbal short-term memory explanation, see de Bree et al., 2007).

In apraxia of speech (AOS), influences of metrical properties (e.g., word stress) on articulation have been widely neglected. In a recent study, Aichert et al. (2016) compared

two-syllabic trochaic words (e.g., *'Puma*, English: puma) with two-syllabic iambs, that is, words with stress on the second syllable (e.g., *Ko'pie*, English: copy). In a word repetition task, it turned out that trochees were produced with a higher accuracy than iambs. The benefit of the regular (= trochaic) pattern was particularly pronounced with regard to rates of segmental errors but was also found in prosodic error counts (i.e., phoneme lengthenings, intra- and intersyllabic pauses). Furthermore, patients seemed to have particular problems in correctly producing the initial (unstressed) syllable of iambic words. The results of our study suggested that, in German, the trochaic meter facilitates articulation in patients with AOS, or, to put it differently, the iambic meter has adverse effects.

The reciprocal effect of trochaic versus iambic patterns on apraxic speech confirms the assumption that segmental and metrical properties are highly interlinked at the phonetic encoding level (e.g., Croot et al., 2010; Fougeron & Keating, 1997). Drawing on the idea of a nonlinear architecture of phonetic plans, we proposed that, at least for German, the strong-weak stress pattern constitutes a particularly stable architecture, in which the lower level gestural and syllabic motor routines for words are organized more coherently than in words with a weak-strong pattern (e.g., Ziegler, 2005, 2009). In other words, combining two syllables to form trochaic words causes particularly low phonetic planning costs (see also Ziegler & Aichert, 2015).

Although clinical research has widely neglected the impact of metrical structure on articulation errors in AOS and aphasic PI, rhythm-based methods have a long tradition in the remediation of these disorders. For example, melody and rhythm are the main basis of the well-known melodic intonation therapy applied in the treatment of persons with severe nonfluent aphasia (e.g., Albert, Sparks, & Helm, 1973). Melodic intonation therapy involves speaking with an exaggerated prosody, characterized by a melodic element (high vs. low tone) and a rhythmic element (short vs. long duration). Stahl, Kotz, Henseler, Turner, and Geyer (2011) compared the contribution of melody and rhythm in patients with nonfluent aphasia, most of whom were diagnosed with AOS. The findings of their study point to the suggestion that rhythm, rather than melody, was crucial for the treatment effects seen in these patients.

Rhythmical cues are also utilized successfully in several other techniques applied in speech sound production treatment, especially AOS therapy. Some of these techniques rely on internal rhythmical cues, such as finger counting (Simmons, 1978) or hand tapping (Square, Martin, & Bose, 2001). Furthermore, a number of studies investigated the effectiveness of external rhythmical cues including vibrotactile stimulation (Rubow, Rosenbek, Collins, & Longstreth, 1982) and auditory metronomic pacing (Dworkin, Abkarian, & Johns, 1988; Shane & Darley, 1978). Wambaugh and Martinez (2000) trained an apraxic speaker by applying a combination of metronomic pacing and hand tapping. Whereas the metronome generates a uniform pace, a metrical pacing technique employed by Brendel and Ziegler (2008) used acoustic pacing signals that were rhythmically

AQ3

adapted to the metrical properties of natural speech. The rhythmical cueing in this study led to improvements in suprasegmental abilities and segmental accuracy, even though the patients received no explicit feedback about the quality of their articulation.

A few studies have also demonstrated the usefulness of rhythmic auditory stimulation in dysarthric speakers. In these patients, rhythmic cues are commonly used as pace-setters, with the aim of reducing speech rate and increasing speech intelligibility (see Mainka & Mallien, 2014). Two studies revealed that dysarthric speakers with severe intelligibility impairments benefit from rhythmic cueing, that is, from metronome pacing and/or rhythmically patterned cueing (Pilon, McIntosh, & Thaut, 1998; Thaut, McIntosh, McIntosh, & Hoemberg, 2001). Furthermore, an auditory priming experiment by Späth et al. (2016) investigated if the metrical regularity of sentences influences speech motor control in individuals with Parkinson's disease. Speech stimuli consisted of metrically regular sentences (comprising four trochaic words) and metrically irregular sentences (comprising alternately trochaic and iambic words). Participants heard a rhythmically regular or irregular sentence spoken by a model speaker (prime) and were subsequently requested to read aloud a rhythmically regular or irregular sentence as a "response" (target). The study showed that speech initiation in individuals with Parkinson's disease was facilitated by a perceived regular speech rhythm. Moreover, they accommodated their speech rhythm to a greater degree to prime sentences with a metrically regular as compared to an irregular pattern. The authors concluded that individuals with Parkinson's disease might benefit from rhythmic auditory stimulation by a regular speech rhythm.

The goal of this study was to examine if patients with AOS and patients with aphasic PI benefit in their production of words from auditory priming by speech with a regular rhythm (prime effect). Moreover, we investigated if the facilitating effect of regular (trochaic) word stress on word production accuracy in patients with AOS, as observed in Aichert et al. (2016), can be replicated (target effect). Furthermore, we asked if the advantage of regular word stress, if present, is confined to impairments at the motor planning stage of speech production (i.e., AOS) or if it also applies to phonological encoding impairments.

AQ4 Method

Participants

Two groups of monolingual German-speaking patients participated in the study. Twelve participants were diagnosed with AOS, all of whom had varying degrees of coexisting aphasia, and 12 participants presented aphasic PIs without AOS. Criteria for participation were as follows: (a) a clear diagnosis of AOS or aphasic phonological output impairment, (b) no or only very mild dysarthria, (c) relatively intact auditory comprehension abilities, and (d) the capability of producing known target words in the

absence of an immediate cue. Eleven further participants who had been recruited in the first instance were excluded because they did not meet all inclusion criteria (e.g., due to the presence of a notable dysarthric impairment or because the speech impairment was too severe for participation).

All participants were right-handed native speakers of German and suffered from a left-hemisphere cerebral lesion (19 ischemic, five hemorrhagic). Background information of the patient sample is summarized in Table 1.

T1

Referral diagnosis concerning the presence or absence of AOS was independently confirmed by two experienced speech and language therapists (first and second authors) on the basis of a sample of spontaneous speech and of word repetition. Confirmation of the clinical diagnosis of AOS was grounded on the following criteria (e.g., Ziegler, 2008): (a) inconsistent occurrence of phonetic distortions and presence of perceived phonemic errors; (b) presence of prosodic disturbances such as syllable segregation, phoneme lengthenings, or inadequate pauses; and (c) visible/audible groping, self-corrections, and effortful speech.

Patients with the diagnosis of an aphasic PI exhibited phonological errors (i.e., well-articulated phoneme substitutions, additions, and deletions) across all tasks requiring a verbal response. Furthermore, these patients had largely intact word-level prosody and a relatively preserved speech rate. This pattern corresponds to the clinical diagnosis of a postlexical phonological disorder (e.g., Maas, Gutiérrez, & Ballard, 2014).

All participants were administered the Aachener Aphasia Test (Huber, Poeck, Weniger, & Willmes, 1983) and the following three subtests of the model-based assessment battery LEMO 2.0 (Lexikon modellorientiert; Stadie, Cholewa, & De Bleser, 2013): Auditory Word Discrimination (Test V1), Auditory Word-to-Picture Matching (Test 11), and Verbal Naming (Test 13). Furthermore, the severity of word repetition impairment was assessed using a modified version of the Hierarchical Word Lists (HWL; Liepold, Ziegler, & Brendel, 2003). The HWL is a word repetition test, comprising, in the modified version used here, 32 picturable nouns varying in syllable length (one- to four-syllable words) and syllable complexity (words with/without consonant clusters). Word production accuracy is assessed for the presence or absence of phonetic distortions, (perceived) phonemic errors, or dysfluencies (initiation problems, intra- or intersyllabic pauses, phoneme lengthenings). The format of the word repetition test HWL was described in more detail in Ziegler (2005, 2009).

According to the Aachener Aphasia Test (Huber et al., 1983), patients in both groups were diagnosed with either a mild or a moderate aphasia. Most patients had no or only mild disturbances of auditory single-word processing abilities as revealed by auditory word discrimination testing (LEMO Test V1) and an auditory word-to-picture matching test (LEMO Test 11). However, whereas only one patient with AOS showed deficits in the auditory discrimination task (mild impairment with six errors/72 test items), six patients in the PI group showed impaired discrimination abilities (between four and 11 errors). Nevertheless, the fact that

Table 1. Demographic details and clinical characteristics of the patient sample.

Demographics and test scores	Apraxia of speech (<i>n</i> = 12)	Phonological impairment (<i>n</i> = 12)
Age in years: <i>Mdn</i> (range)	55 (30–78)	60 (41–73)
Months postonset: <i>Mdn</i> (range)	63 (2–191)	6 (1–97)
Etiology	9 ischemic, 3 hemorrhagic	10 ischemic, 2 hemorrhagic
Severity of aphasia ^a	7 mild, 5 moderate	5 mild, 7 moderate
Word repetition accuracy ^b		
Phonetic	44 (2–75)	93 (73–100)
Phonemic	64 (19.94)	78 (29–96)
Fluency	59 (6–90)	78 (42–98)
Auditory Word Discrimination (LEMO, ^c Test V1)	10 unimpaired, 1 at threshold, 1 impaired	6 unimpaired, 6 impaired
Auditory Word–Picture Matching (LEMO, ^c Test 11)	8 unimpaired, 2 at threshold, 2 impaired	7 unimpaired, 3 at threshold, 2 impaired
Oral Naming ^d (LEMO, ^c Test 13)	3 unimpaired, 9 impaired	1 unimpaired, 2 at threshold, 9 impaired

^aAccording to the profile height of the Aachener Aphasia Test (Huber et al., 1983). ^bPercentage of correct items in the modified Hierarchical Word Lists Test (Liepold et al., 2003): *Mdn* (minimum–maximum). ^cSubtests of LEMO (Stadie et al., 2013). ^dResponses with errors on only one phoneme (e.g., [ʔ•••], English: *dress* → [ʔ•••]) were scored as correct.

the aphasic patient with the highest error rate in this task presented with only minimal limitations in auditory word comprehension (two errors/20 items, performance at threshold) may suggest the involvement of metalinguistic demands in the discrimination task. Word discrimination requires explicit phonemic segmentation skills (as well as particular working memory capacities), which are not a requisite skill for word comprehension or word repetition (see also Wunderlich & Ziegler, 2011). Therefore, in all patients, auditory discrimination abilities were considered sufficient to accomplish the sentence completion task administered in this study.

An oral picture-naming test (LEMO Test 30) revealed similar performances in both patient groups. Whereas three patients in each group had no or only minimal impairment (zero to two errors), nine patients in each group showed scores between three and 11 errors (out of 20 items). Because errors in oral naming included several semantic paraphasias (e.g., *Kran*, English: *crane* → *Bagger*, English: *excavator*), one might suspect that some lexical access deficit was present in these patients. However, the preserved word comprehension abilities in the LEMO Test 11, which includes the same items as the oral picture-naming task, point at largely intact lexical–semantic processing abilities. Furthermore, because in the experimental sentence completion task reported here, semantic errors constituted only a very small proportion of the observed errors (AOS: 0.7%, PI: 2.2%), we assume that the patients' performance in the auditory priming experiment reported here was primarily affected by the apraxic impairment or the (postlexical) PI, respectively. Notably, in the word repetition test HWL, the patients produced not a single semantic paraphasia.

Regarding word repetition accuracy in the HWL testing, patients with PI were overall less impaired than patients with AOS (see Table 1). The difference was most pronounced in the percentage of phonetic distortions and was least pronounced in the percentage of (perceived) phonemic errors. When all three error types (i.e., phonetic distortions, perceived phonemic errors, and dysfluencies) were entered into a linear discriminant analysis, a complete separation of the two groups was achieved, with 100% correct allocations

of the participants, $\chi^2(3) = 30.1, p < .001$. This can be considered as an independent validation of the patient classification underlying this study. A group of 36 neurologically healthy speakers (18 men and 18 women) between 30 and 70 years of age ($M = 49.7$ years) also participated in this study (NOR).

Auditory Priming Task

Materials

The speech material comprised 96 sentences consisting of five 2-syllabic words each. The first four words of each sentence served as a prime; the last word was the target word to be produced by the participant. The item set was arranged in four different prime–target conditions, which were varied according to the metrical regularity of the prime sentence and the metrical regularity (i.e., word stress) of the target word. Regular prime sentences consisted of a series of four trochaic words (i.e., an alternating strong–weak pattern), whereas irregular prime sentences contained an alternation of trochaic and iambic words (trochee–iamb–iamb–trochee). Target words were either trochees (regular) or iambs (irregular). There were four different conditions (see Table 2 for examples): (a) Xx Xx Xx Xx–Xx: regular prime sentence–trochaic target word, (b) Xx Xx Xx Xx–xX: regular prime sentence–iambic target word, (c) Xx xX xX Xx–Xx: irregular prime sentence–trochaic target word, and (d) Xx xX xX Xx–xX: irregular prime sentence–iambic target word.

The materials contained 48 target words (24 trochees, 24 iambs), each of which occurred in both a regular and an irregular prime sentence. By this procedure, differences in item difficulty between the targets in the regular versus irregular prime condition were avoided. The trochaic and iambic target words were also counterbalanced for the sound class of the first phoneme and included only CV (consonant–vowel) and CVC syllables. Furthermore, all target items were monomorphemic nouns of low lexical frequency (< 10 spoken/written per million; CELEX database; Baayen, Piepenbrock, & Gulikers, 1995). Though no

AQ5

T2

Table 2. Overview of the four experimental conditions, with examples.

Condition	Prime sentence (with literal translation)	Target word
R-R	Regular (Xx Xx Xx Xx) 'Lena 'pflanzte 'damals 'diese (English: Lena planted then this)	Regular (trochee / Xx) 'Tulpe tulip)
R-I	Regular (Xx Xx Xx Xx) 'Friedrich 'neckte 'häufig 'diesen (English: Friedrich teased often this)	Irregular (iamb / xX) Te'nor tenor)
I-R	Irregular (Xx xX xX Xx) Jule vér'schenkt je'doch 'diese (English: Jule gives away though this)	Regular (trochee / Xx) 'Tulpe tulip)
I-I	Irregular (Xx xX xX Xx) 'Mira be'trog zu'nächst 'diesen (English: Mira cheated at first this)	Irregular (iamb / xX) Te'nor tenor)

Note. R = metrically regular; I = metrically irregular.

AQ6 item had a lexical frequency over 10 per million, the iambs had slightly higher frequencies ($Mdn = 4.2$) compared to the trochees ($Mdn = 2.2$).

To ensure that the prime sentences (especially the verbs) had little semantically predictive relationship to the target words, a written sentence completion (“cloze”) task with 43 healthy volunteers (28 women, 15 men; $M_{age} = 41.8$ years) was conducted. Participants were instructed to complete each sentence fragment (i.e., the prime) with the first word they thought of. In 83 of the 96 sentences, none of the participants chose the target noun to fill the cloze; in 10 cases, only one or two out of 43 raters used the target word specified for the experiment, whereas in one sentence, six of 43 responders were on-target. Only one target word appeared to be relatively predictable in the context of the prime sentence, with 22 of 43 mentions in both the regular and irregular prime conditions. In these two items, the verbs in the original sentences were exchanged to make the target words less predictable.

Stimulus Preparation

Each sentence, including the target word, was produced by two experienced speakers and recorded using an audio interface (Focusrite Scarlett 2i2) and a Rode NTG-2 microphone. First, a male speaker read each full sentence at a moderate speaking rate. In a second step, a female speaker was presented these sentences via headphones and was required to repeat each of them by adjusting her speaking rate and style to the male model speaker. To ensure that average speaking rates (in syllables per second) were similar across the four conditions, some of the stimuli of both model speakers were adjusted by minimally shortening or lengthening pauses or segments. After these manipulations, there was no significant effect of experimental conditions on speaking rate, one-way analysis of variance, $F(3, 95) = 0.561, p > .1$.

In a last step, the target words were spliced out from the female speaker's sentences using the Praat editor (Boersma & Weenink, 2013). The remaining sentence fragments served as primes in the sentence completion task described below.

Procedure

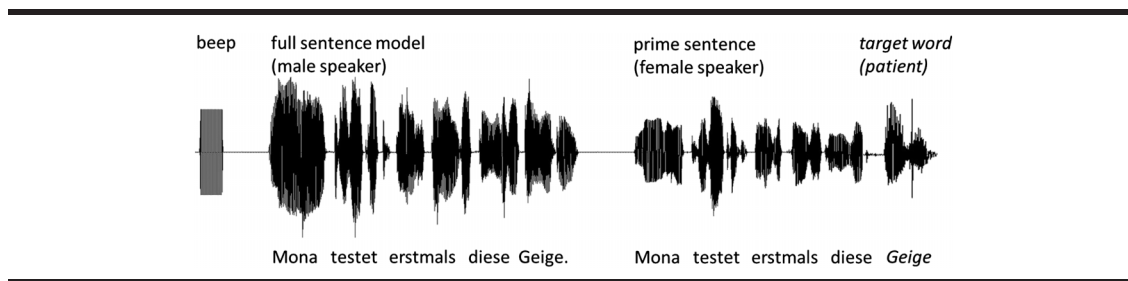
A sequential synchronization paradigm based on a sentence completion task was conducted. In a first run, after a beep signal, the participants heard the male model speaker producing the whole sentence, including the target word (full sentence model). This stimulus was primarily used to familiarize participants with the target word to be produced in the trial. After a pause of 600 ms, the same sentence spoken by the female model speaker, with the target word spliced out (i.e., the *prime*), was presented, and participants were required to complete the prime sentence fragment with the target word. Participants were invited to join in by maintaining the rhythm and the fluency of the female auditory model. By this paradigm, we tried to avoid a pure repetition mode of word production and, instead, simulate a dyadic interaction between two speakers—though admittedly in a rather experimental format. For an illustration of the procedure, see Figure 1.

F1

The experiment was implemented on a computer using PsychoPy (Psychophysics software; Peirce, 2007). Stimuli were presented via mobile loud speakers (Philips multimedia speakers 2.0). New trials were always initiated manually by the experimenter. The participants' responses were recorded digitally at a sampling rate of 44.1 kHz, using a Rode NTG-2 microphone and an audio interface (Focusrite Scarlett 2i2). Audio recordings were started immediately at the beginning of each trial, comprising the starting beep, the two model speakers' sentences, and the participant's production of the target word. Recordings were stored on the hard disk of a computer.

The 96 sentences were presented in a pseudorandomized order. Stimulus order was adjusted manually to ensure that no more than two trochaic or two iambic target words occurred in succession and that prime sentences with the same metrical structure (regular or irregular) did not occur more than three times in a row. Furthermore, to avoid learning effects or perseverations, the distance between two occurrences of the same target word had to be more than 30 trials.

The experiment was divided into two sections of 48 sentences each. The break between the two runs was

Figure 1. Illustration of the sequential synchronization paradigm.

filled with subtests from the LEMO battery (Stadie et al., 2013; see Table 1). Before starting with the experimental items, the patient was familiarized with the procedure using four practice items embedded in a PowerPoint presentation. The patient was allowed to repeat the practice items as often as necessary until he or she was familiar with the experimental task.

Data Analysis

Auditory analyses of participants' responses were performed by the second author. Because the healthy controls (NOR) made a negligibly small amount of errors in the sentence completion task (only four individuals produced one segmental error each, namely additions in 'Geige → Geigen, Te'nor → Tet'nor and elisions in 'Gabel → 'Gabe, 'Pater → 'Pate), they were not included in the error analyses. The patients' reactions were transcribed using broad phonetic transcription. Symptoms such as phonetic distortions or prosodic deviations that were not captured by the transcription system were marked with diacritical signs. In cases of self-corrections or repeated attempts, the first full word production was analyzed. In a first step, the transcripts were scanned for segmental errors (perceived phoneme errors or phonetic distortions), prosodic errors (phoneme lengthenings, intra- and intersyllabic pauses), and searching behaviors (articulatory groping or phonemic searching). Perceived phoneme errors comprised elisions and phonetically well-articulated substitutions, transpositions, or additions of phonemes. Phonetic distortions were marked if phonetical alterations occurred on targeted sounds. We refrained from subclassifying phonetic distortions any further. Prosodic errors were marked if lengthenings locally restricted to single positions within a target word or inter- or intrasyllabic pauses were observed. In a first analysis, the whole target word was considered as the error unit; that is, multiple deviations on a word were counted as a single error. In a second step, segmental errors were analyzed in the first and second syllables separately.

To test the reliability of the second author's transcripts, 32 words each from three patients with AOS and 32 words each from three patients with PI (i.e., a total of 192 words) were reanalyzed by an independent transcriber (the first author). There was an almost perfect interrater agreement (kappa statistics; Landis & Koch, 1977) between the two transcribers for all error categories, that is, for

segmental errors, prosodic errors, and searching behavior (in all cases $\kappa > .83$, $p < .001$).

Rhythm Discrimination Task

To assess if participants could detect the metrical differences between the two priming conditions (i.e., regular vs. irregular metrical primes), a rhythm discrimination task was developed (for a similar procedure, see Späth et al., 2016).

Stimuli

Two sequences of harmonic tones representing the regular and irregular prime sentences of the sentence completion experiment were created using Praat (Boersma & Weenink, 2013). Each single tone was synthesized by superimposing a sine wave of 210 Hz ("high") or 195 Hz ("low") by five harmonics of exponentially decreasing intensity levels. A "trochaic" tone pair was then created by combining a high tone of 410-ms duration ("stressed") with a low tone of 220-ms duration ("unstressed"), with a 35-ms pause in between. Likewise, an "iambic" pair was created by combining a low tone of 140-ms duration ("unstressed") with a high tone of 470-ms duration ("stressed"), with a pause of 45 ms in between. Both pairs had the same overall duration of 655 ms. Trochaic and iambic tone pairs were then combined to match the rhythmically regular and irregular patterns of the prime sentences in the sentence completion task (regular: Xx Xx Xx Xx, irregular: Xx xX xX Xx).

Procedure

Regular and irregular tone sequences were presented in pairs, with a 75-ms pause in between two stimuli. Each combination of regular and irregular sequences (i.e., R-R, R-I, I-R, I-I) was presented eight times in a randomized order. The average loudness level of each stimulus was set to 85 dB. Participants were instructed to judge, by pressing a key on the computer keyboard, whether two consecutive tone sequences were the same or different. The rhythm discrimination experiment was administered after the sentence completion experiment.

Statistics

Dependent variables in the sentence completion task were (a) segmental word errors, (b) prosodic word errors, (c) searching behavior, (d) segmental syllable errors of

Syllable 1, and (e) segmental syllable errors of Syllable 2. In the rhythm discrimination task, response errors served as dependent variables.

Generalized linear mixed-effects models (GLMMs) were calculated to estimate the effects of prime regularity (factor PRIME) and target regularity (factor TARGET) on error outcomes in the two groups (factor GROUP), with ITEMS as random intercepts and SUBJECTS as random slopes. Because all dependent variables were binary, the data were fitted using the logit link function. By including random slopes of SUBJECTS by PRIME and by TARGET, we not only controlled for the variability within versus between groups but also were able to calculate estimates of the effects each of the two fixed factors had on each individual participant. All calculations were performed in R using the glmer function of the lme4 package (Bates, Mächler, Bolker, & Walker, 2015).

Results

Auditory Priming Task

Unclassified Responses

In the patients, 180 of 2,304 responses (7.8%) were discarded as unclassifiable. Exclusions were mainly due to complete null reactions ($n = 70$) or to fragmentary responses following articulatory groping or phonemic searching behavior ($n = 48$). Furthermore, patients produced phonologically related word errors ($n = 27$), semantic errors ($n = 19$), and perseverations of preceding target words ($n = 16$). There were similar amounts of unclassified errors on the targets following regular ($n = 93$) and irregular ($n = 87$) prime sentences. However, with regard to the regularity of the target words, there were many more unclassified errors on the iambic than on the trochaic words (trochaic: $n = 58$, iambic: $n = 122$). In total, patients with PI produced nearly twice as many unclassified errors compared to the AOS group (PI: 118 errors vs. AOS: 62 errors).

In the following error analyses, a total of 2,124 word reactions could be included. For all error categories, we conducted a GLMM with the fixed effects PRIME (regular, irregular), TARGET (trochee, iamb), and GROUP (AOS, PI); the random intercepts ITEM; and the random intercepts and slopes of SUBJECT by PRIME and by TARGET. Random slope effects for SUBJECTS were included to account for the within-group variability of metrical effects.

Word-Based Errors

Segmental errors. Figure 3 depicts mean segmental error rates (i.e., phoneme distortions or perceived phoneme errors) in patients with PI and AOS across the two prime and the two target conditions (regular and irregular, respectively). In general, the patients with AOS produced more errors (54%) than the PI group (30%), which reflects different degrees of severity of their sound production impairments. Across the two groups, the overall rate of segmental errors was correlated significantly with the rates of phonetic ($r = .67$, $p < .001$) and phonemic ($r = .84$,

$p < .001$) errors of the clinical word repetition test HWL (cf. Table 1).

Figure 2 also shows a clear influence of the regularity of the target word on segmental errors. In both groups, higher error rates occurred on the iambic as compared to the trochaic items. Average segmental error rates were 52% in the trochees versus 34% in the iambs. Prime regularity also seemed to have an impact on error rates. Average segmental error rates were 40% in the targets following regular primes versus 45% following irregular primes. In the AOS group, the advantage of trochaic over iambic target words was smaller in the irregular as compared to the regular PRIME condition. The lowest error rates were observed in the condition where the regularity of the target word matched the regularity of the prime sentence.

In order to test whether any interactions between the three factors GROUP, PRIME, and TARGET need to be included in the modeling of the data, a full GLMM (including all two- and three-way interactions) was contrasted with a model specifying only main effects. Because a comparison of the two models with a likelihood ratio test (using the analysis of variance function in R) revealed that the inclusion of interaction terms did not improve the explanatory power of the model, $\chi^2(4) = 1.59$, $p > .05$ (see Table 3, Column 1), all interaction terms were excluded. A likelihood ratio test of the main-effects-only model versus the null model (i.e., the model with the same random effects, but no fixed effects) was significant (see Table 3, Column 2), demonstrating that the three factors influenced the data significantly. The model revealed a significant GROUP effect, with an estimated increase of the log odds of segmental word errors in the AOS group relative to the PI group of 1.37 ($p < .01$; see Table 3, Column 3). Moreover, the log odds of errors on irregular versus regular target words (factor

Figure 2. Word-based segmental error rates (means, 95% confidence intervals) as a function of prime and target regularity. Left: patients with apraxia of speech (AOS); right: patients with phonological impairment (PI).

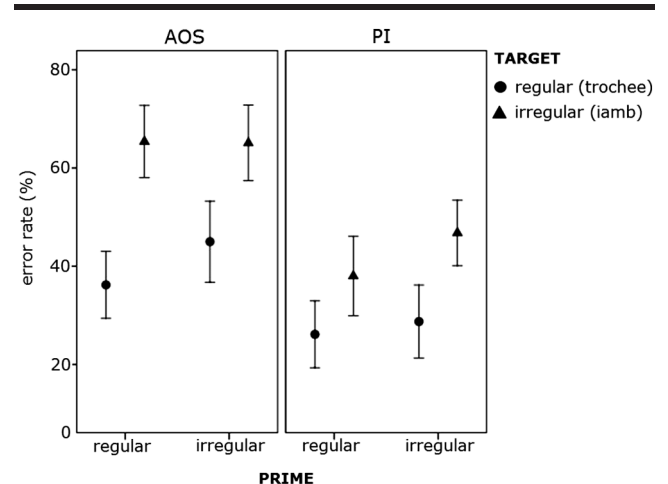


Table 3. Overview of the generalized linear mixed-effects models calculated for all error categories.

	Interactions ^a	Difference from null model ^b	GROUP ^c	TARGET ^d	PRIME ^e
Segmental word error	1.59 <i>ns</i>	29.8***	1.37**	1.10***	.29**
Prosodic word error	5.43 <i>ns</i>	10.0*	2.51**	.54 <i>ns</i>	-.01 <i>ns</i>
Searching behavior	3.11 <i>ns</i>	15.66**	-.48 <i>ns</i>	.71***	.23 <i>ns</i>

^a χ^2 Value of likelihood ratio test of full model versus model without interaction terms. ^b χ^2 Value of likelihood ratio test of null model versus model without interaction terms. ^cEstimate of β coefficient (log odds ratio). Reference category: group with phonological impairment. ^dEstimate of β coefficient (log odds ratio). Reference category: regular target word. ^eEstimate of β coefficient (log odds ratio). Reference category: regular prime sentence.

* $p < .05$. ** $p < .01$. *** $p < .001$. *ns* = not significant.

TARGET) were significantly increased by 1.10 ($p < .001$; see Table 3, Column 4). Finally, there was also a significant (though weaker) effect of the factor PRIME on error likelihood, with an estimated increase of log odds by 0.29 in items with irregular primes (see Table 3, Column 5).

Although there was no significant three-way interaction (potentially due to a lack of statistical power), we tested whether the interaction between prime and target, which was so apparent in the AOS data (see Figure 3, left), was significant when the model was applied to only the AOS group. In this analysis, there was a significant effect in the sense that the likelihood of a segmental error to occur dropped by a log odds ratio of -0.65 ($p < .05$) when regular words were primed by regular sentences.

In order to examine the within-group variation of the metrical effects upon segmental accuracy, the estimates of the individual slopes of the random effects of SUBJECT by PRIME and by TARGET regularity were extracted. Positive slopes indicate an increase in the likelihood of a segmental error to occur in irregular as compared to regular prime sentences or target words, respectively.

Regarding the PRIME effect, individual slopes were all positive in both groups and ranged within narrow limits,

indicating a very consistent (though small) influence of the metrical regularity of the prime sentences (see Table 4) and demonstrating that the fixed effect of PRIME was consistently present in the participants of both groups. Regarding the TARGET effect, individual slopes had a considerably higher magnitude and a higher variability but were also consistently positive, with the exception of two outliers with rather flat negative slopes in the PI group (see Table 4).

In search of factors influencing a patient's sensitivity to metrical regularity, slope estimates were correlated with the diagnostic variables of Table 1, with the rhythm discrimination scores of Figure 6, and with overall error rates in the auditory priming task. The auditory processing and picture-naming scores of the LEMO tests had no effect on individual slope estimates, neither for the PRIME nor for the TARGET factor (absolute $r < .40$, $p > .05$). There was also no influence of the rhythm discrimination performance ($r < .22$, $p > .05$). Significant effects were only obtained for measures of word repetition accuracy upon the by-PRIME slopes (phonemic error scores of the HWL: $r = .78$, $p < .001$; average segmental error rate of the auditory priming experiment: $r = .84$, $p < .001$). Hence, the influence of the irregularity of prime sentences was stronger in patients with more severe sound production problems. Despite their larger magnitudes and their overall higher variability, the individual by-TARGET slopes of the random effects factor SUBJECT did not show significant correlations with any of the measures of aphasic or speech impairment assessed here.

Prosodic errors. A prosodic error of target word production was transcribed if (a) one or several phonemes of the word were lengthened, (b) intrasyllabic or intersyllabic pauses occurred, or (c) the word's stress pattern was altered. In general, patients with PI produced particularly low rates of prosodic errors at the level of the single word production examined here (6% on average). Prosodic error rates in patients with AOS were higher (23% on average), but still rather low compared to segmental error rates. Rates of prosodic errors in the experimental task were significantly correlated with the fluency scores of the clinical word repetition test HWL ($r = .77$, $p < .001$; see Table 1).

On average, 13% of all trochees and 16% of all iambs were affected by prosodic errors. Notably, only a very small number of words ($n = 7$) were misstressed. In all of these observations, an iambic target word was realized with a

Figure 3. Word-based prosodic error rates (means, 95% confidence intervals) as a function of prime and target regularity. Left: patients with apraxia of speech (AOS); right: patients with phonological impairment (PI).

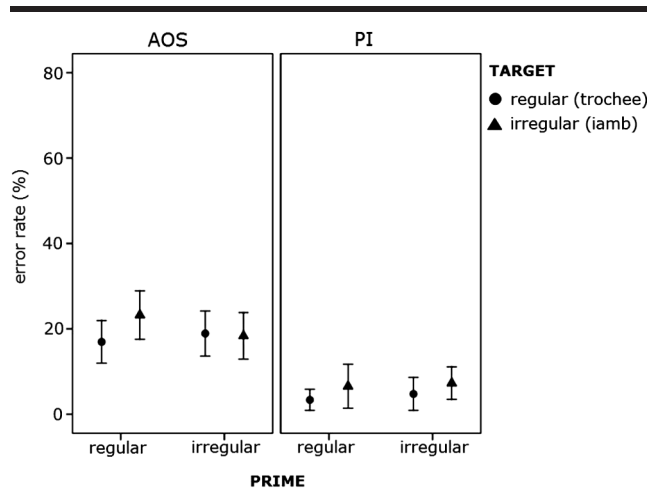


Table 4. Distributions of individual slope estimates (log odds ratios) of the random-effects factor SUBJECT by PRIME and by TARGET.

Fixed factor		AOS	PI	t Test
PRIME	<i>M</i> ± <i>SD</i>	0.29 ± 0.04	0.29 ± 0.03	<i>ns</i>
	<i>Mdn</i> (min, max)	0.28 (0.24, 0.35)	0.28 (0.23, 0.36)	
TARGET	<i>M</i> ± <i>SD</i>	1.17 ± 0.71	0.98 ± 0.69	<i>ns</i>
	<i>Mdn</i> (min, max)	0.80 (0.36, 2.21)	1.12 (−0.20, 1.93)	

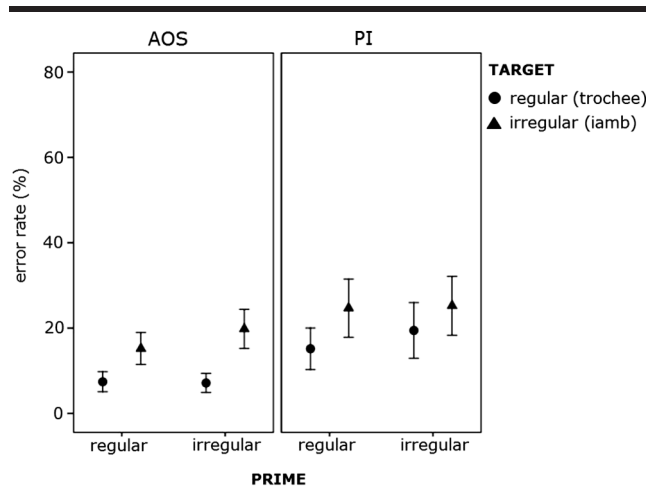
Note. Positive values indicate that the likelihood of an error to occur is higher in the irregular than the regular condition. AOS = apraxia of speech; PI = phonological impairment; *ns* = not significant.

trochaic stress pattern. The seven word stress errors occurred in four patients with AOS.

As in the case of the segmental word errors, a full GLMM for prosodic errors did not explain significantly more of the variance in the data than a restricted model containing no interaction terms (see Table 3, Column 1), and the restricted model was significantly better than a null model (see Table 3, Column 2). Among the three factors, only the factor GROUP had a significant effect, with an increase of error likelihood (in terms of log odds) of 2.55 in the AOS relative to the PI group. There were no significant influences of the factors TARGET and PRIME on error likelihood (see Table 3, Columns 3–5). Because of the absence of regularity effects on prosodic errors, the within-group variation of random slope estimates was not analyzed.

Searching behavior. As searching behavior, we considered articulatory groping (as a typical AOS symptom) or phonemic searching behavior (as a PI symptom; see Figure 4). Percentages of searching behavior for the two groups across the two prime and the two target conditions are presented in Figure 5. At first glance, the results displayed in Figure 5 show an influence of the regularity of the target word. Patients with AOS and patients with PI produced more searching behavior on iambs (19%) than on trochees (12%).

Figure 4. Searching behavior rates (means, 95% confidence intervals) as a function of prime and target regularity. Left: patients with apraxia of speech (AOS); right: patients with phonological impairment (PI).

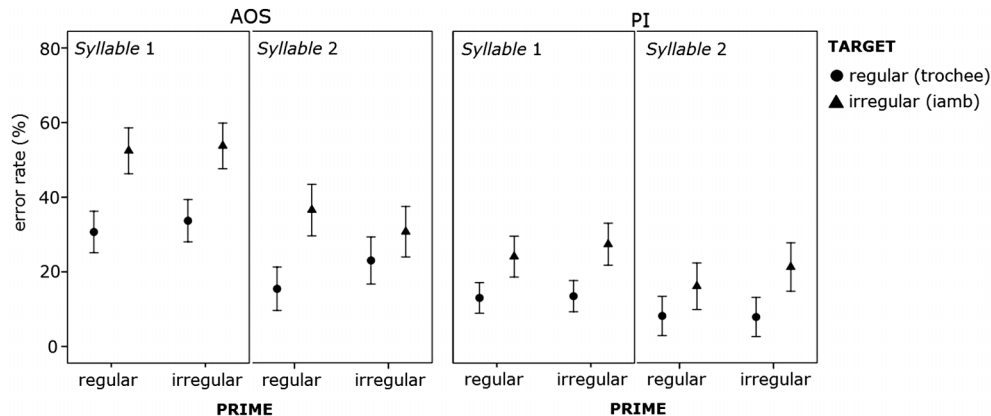


The results of a GLMM analysis are listed in Table 3 (Line 3). Again, there were no significant interactions. A GLMM restricted to main effects of GROUP, TARGET, and PRIME fitted the data significantly better than a null model. The only factor that influenced the likelihood of searching behavior to occur was TARGET, with a significant increase in irregular versus regular target words (see Table 3, Column 4). Regarding the consistency of this result within groups, all participants had positive slopes between 0.47 and 1.12 ($M = 0.71$, $SD = 0.17$). None of the clinical variables listed in Table 1 was correlated with the size of individual target regularity effects, as measured by slope estimates, but there was a weak, though significant, positive effect of the overall amount of searching behavior documented in the auditory priming experiment ($r = .42$, $p < .05$). The stronger a patient's overall searching behavior was, the more sensitive was he or she to the irregularity of target words.

Position-dependent segmental errors. Segmental errors observed on the first and second syllables of the target word are depicted in Figure 6. On average, patients with AOS produced more errors on the first relative to the second syllable (42% vs. 33%), whereas there was no difference in patients with PI (19% vs. 21%). The figure also shows an influence of the regularity of the target word. In both groups and both positions, higher error rates occurred on the iambic as compared to the trochaic items. Average error rates on the first syllable were 23% in the trochees versus 40% in the iambs; average error rates on the second syllable were 22% in the trochees versus 33% in the iambs.

The data were fitted by a GLMM including SYLLABLE NUMBER as a further fixed effects factor. Likelihood ratio tests comparing the full GLMM with a model excluding all three-way and four-way interactions and with the null model revealed that there were no significant higher interactions, $\chi^2(5) = 6.3$, $p > .10$, and that the restricted model yielded a significant fitting of the data, $\chi^2(10) = 69.8$, $p < .001$. Overall, the AOS group had higher error rates (estimated log odds ratio: 1.32, $p < .01$), and there was again a main effect of the regularity of the target word (estimated log odds increase by 1.10 of irregular target words, $p < .001$). There was no significant effect of the factor PRIME. The observation that remarkably higher error rates on the first syllable occurred in the AOS but not the PI group was confirmed by a significant interaction, with a log odds ratio of -0.73 in Syllable 2 of patients with AOS ($p < .001$). As a further two-way interaction, the TARGET effect turned

Figure 5. Segmental syllable error rates (means, 95% confidence intervals) as a function of prime and target regularity. Left: patients with apraxia of speech (AOS); right: patients with phonological impairment (PI).

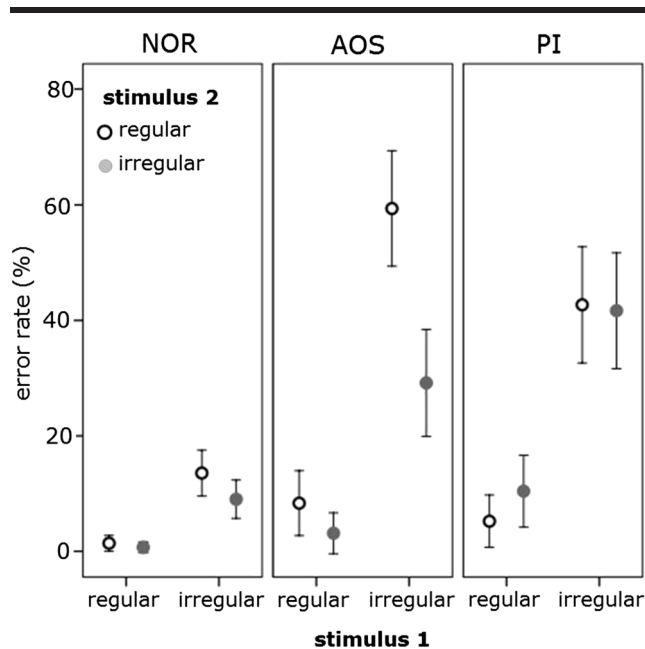


out to be smaller in the second than in the first syllable (estimated log odds ratio: -0.35 , $p < .05$).

Rhythm Discrimination Task

Figure 6 shows mean error rates for the four conditions (regular–regular, regular–irregular, irregular–regular, and irregular–irregular). On the whole, neurologically healthy individuals made only 6% errors, whereas the two patient groups made 25% errors overall. All groups produced considerably fewer errors when the first stimulus was regular.

Figure 6. Error rates (means, 95% confidence intervals) in the rhythm discrimination task for the patients (with apraxia of speech [AOS] and phonological impairment [PI]) and the control group (NOR). Comparison of the four discrimination conditions (regular–regular, regular–irregular, irregular–regular, and irregular–irregular).



A GLMM was calculated using STIMULUS 1 (regular, irregular), STIMULUS 2 (regular, irregular), and GROUP (NOR, AOS, PI) as fixed effects and SUBJECT as random intercept effect. Because the full model fitted no better than a model containing only two-way interactions, $\chi^2(2) = 0.84$, $p > .10$, the three-way interaction was not included. A further reduction of model complexity was achieved by excluding the two-way interaction of GROUP $\times$ STIMULUS 1 without losing explanatory power, $\chi^2(4) = 2.20$, $p > .10$, which demonstrates that the increase of error rates when STIMULUS 1 was irregular was statistically the same for all three groups. Though the influence appears smaller for the healthy controls than for the two patient groups in Figure 6, the proportionate increase of errors was even higher in the healthy individuals (Factor 11) as compared to patients with AOS (Factor 8) and with PI (Factor 5).

The reduced model confirmed significantly higher error rates in both patient groups relative to the control participants, with an estimated increase of the log odds of discrimination errors of 2.34 in the AOS group and of 2.16 in the PI group ($p < .001$). The AOS and PI groups were not different (estimated log odds ratio: -0.44 , $p > .10$). Regarding the influence of the regularity of the first stimulus of the discrimination pair, the log odds of errors was significantly increased by 2.84 when STIMULUS 1 was irregular ($p < .001$). There was no main effect of STIMULUS 2, but a significant interaction with GROUP, with a significant decrease of error rates specifically in the AOS group when STIMULUS 2 was irregular.

The absence of an interaction of STIMULUS 1 with GROUP reflects that the condition in which the first stimulus contained an irregular tone sequence was particularly difficult for all groups. The interaction of STIMULUS 2 with GROUP reflects that, for this position, the difference between the regular and the irregular conditions was only remarkable in patients with AOS. In contrast, error rates of patients with PI and controls were not sensitive to the regularity of the second stimulus.

Discussion

The first aim of this study was to investigate if word production in patients with AOS and in patients with PI benefits from auditory priming by speech with a regular rhythm. To this end, patients were presented prime sentences with a regular (series of trochaic words) or an irregular (alternation of trochaic and iambic words) rhythmical pattern, respectively, before they produced single target words. Second, we wanted to determine if the metrical pattern of the target words to be produced in the two priming conditions influences speech accuracy and speech fluency in these patients. To answer this question, the target words following the prime sentences had either a trochaic or an iambic pattern. The sentence completion task used here involved participants as listeners and speakers at the same time, thereby creating an experimental situation of two interacting speakers.

Prime Effect

Regarding our first research goal, the outcome of this study revealed an influence of the metrical regularity of speech input, both in patients with AOS and in patients with PI. The participants of the two patient groups were very consistent in producing fewer segmental errors on target words preceded by regularly stressed prime sentences as compared to prime sentences with a more irregular metrical pattern. They therefore seemed to exploit rhythmic cues in speech for the initiation and the segmental realization of the target words. Obviously, perception of a regular speech rhythm facilitated speech motor and phonological planning in a specific way. The PRIME effect turned out to be stronger in patients with more severe sound production impairments. In patients with AOS, the interaction between perceiving and producing speech was strongest when prime sentences and target words matched in their trochaic metrical pattern.

In a general sense, the influence of speech input on production observed here is consistent with the assumption of a close link between perceiving and producing speech. Originally, the idea of a mapping of auditory input onto motor representations has been a core claim of the motor theory of speech perception (Liberman & Mattingly, 1985; cf. Galantucci et al., 2006, for a more recent review). The link between speech perception and production has since then been examined in numerous studies (e.g., Fadiga, Craighero, Buccino, & Rizzolatti, 2002; Jarick & Jones, 2009; Watkins, Strafella, & Paus, 2003). Watkins et al. (2003), for example, used transcranial magnetic stimulation to demonstrate that listening to speech enhances the excitability of the speech motor system in healthy speakers.

Considering that the sentence completion task administered here required participants to adapt to a perceived model speaker, an even stronger interaction of auditory with motor information was expected to occur. This expectation was driven by considerations that, in naturalistic situations, speaker–listener interactions may enhance

activation of the motor system during listening, thereby promoting widely known behaviors like mutual adaptation and coordination in spoken conversation. In an opinion paper, Scott, McGettigan, and Eisner (2009) considered the motor and premotor cortices to play a significant role in the auditory–motor processes implied in the mutual adaptation of two interacting speakers during conversation, mediated by input from superior temporal areas via the auditory dorsal pathway. This structure has been described earlier as a neural basis of phonetic convergence (Kappes, Baumgaertner, Peschke, & Ziegler, 2009; Peschke, Ziegler, Kappes, & Baumgaertner, 2009). In a rather general sense, investigations of immediate speaker–listener interactions are part of a broader research into self–other motor interactions, which has revealed that the brain’s motor system is facilitated by observations of others (e.g., Jackson & Decety, 2004; Schütz-Bosbach, Mancini, Aglioti, & Haggard, 2006).

It is another possibility that participants in our study were more rhythmically entrained to the regular than the irregular speech stimuli. Rhythmic entrainment is a process generating sensorimotor predictions about upcoming rhythmic structure, allowing humans to synchronize their actions very precisely with the rhythm of external stimuli (e.g., Large & Jones, 1999; Repp, 2005). For example, rhythmic entrainment is considered one of the key mechanisms in synchronizing movements with the musical beat and rhythm during music listening, dancing, or music making with others (e.g., Dalla Bella, Białuńska, & Sowiński, 2013). In conversation, rhythmic entrainment may also play a role, because predictions about another speaker’s utterances for rhythm and rate enable a listener to anticipate the end of a speaker’s turn and thereby facilitate smooth turn taking (Scott et al., 2009). Several experimental studies have shown that neural entrainment, that is, phase locking of neural oscillatory activity to the periodicity of an external stimulus, is an underlying mechanism of rhythmic priming, thereby enhancing speech perception and production abilities (e.g., Cason, Hidalgo, Isoard, Roman, & Schön, 2015; Cason & Schön, 2012; Falk, Lanzilotti, & Schön, 2017). For example, Falk et al. (2017) observed stronger neural entrainment to speech preceded by nonverbal, rhythmically regular as compared to irregular primes. They speculated that listening to metrically regular speech may also establish rhythmic expectations, which, in turn, might facilitate speech production processes.

On the background of these theoretical considerations, the regular primes in the present experiment, compared to the irregular primes, may have enhanced rhythmic and neural entrainment in our participants, thereby generating temporal predictions and freeing attentional resources that allowed for more correct speech production. Or, as neural and motor entrainment to regular rhythmic structure continues even after the sensory stimulation ceases (Repp & Su, 2013), speech movements embedded in a metrically compatible “template” with the previous auditory structure may have been facilitated in our experiment.

In line with this latter possibility, the regular prime advantage manifested itself in a smaller number of segmental

AQ8
AQ9

errors, demonstrating the entrenchment of segmental articulation in metrical rhythm, as predicted by the “Prosody First” framework outlined by Keating (2006). In patients with AOS, the largest effect occurred in the condition where a rhythmically regular prime was followed by a regular target, as one would expect, but the regular prime facilitation was sufficiently robust to arise across the board of both the trochaic and the iambic targets.

From a clinical perspective, the influence of the metrical properties of a perceived sentence on word production seen in this study is not entirely new. It is compatible with observations from several treatment studies showing that rhythmical cues can improve production abilities in patients with AOS (e.g., Brendel & Ziegler, 2008; Wambaugh & Martinez, 2000). However, this is the first study demonstrating that the regular rhythm of natural speech rather than that of nonverbal stimuli, such as a metronome, can enhance speech production in patients with AOS. Furthermore, rhythmic facilitation effects in aphasic patients with PI have, to our knowledge, never been reported before.

In order to control for purely perceptual effects, we tested both patient groups and a control group on a rhythm discrimination task to determine if they could detect differences between the regular and irregular primes. All three groups performed better in the conditions in which the first stimulus was a regular tone sequence. This result is consistent with the rhythmic entrainment literature (see above), in that the regularity of the first stimulus in our experiment might have induced implicit rhythmic expectations facilitating the comparison with the rhythmical pattern of the second stimulus. However, the two patient groups turned out to have considerable problems when the first stimulus of a pair consisted of an irregular sequence. Even though we had not predicted such an amount of errors to occur, the outcome of this experiment showed that the patients were sensitive to the rhythmical properties of the stimuli. More specifically, the data provide further evidence that the participants, most of all the patients, benefited from perceiving a regular rhythmic pattern. We have no convincing explanation for the observation that only the apraxic speakers were sensitive to the regularity of the second stimulus (with a poorer performance on regular tone sequences). One might speculate that irregular tone sequences in the second position were perceptually more salient for these patients.

Target Effect

Earlier investigations based on repetition tasks had revealed that the regular metrical pattern in German (trochee), unlike the iambic pattern, facilitates articulation in patients with AOS (Aichert et al., 2016; Ziegler & Aichert, 2015). In this study, the advantage of trochaic words could be replicated quite convincingly, considering that this investigation was based on a new patient group of 12 apraxic speakers and also on a new paradigm (sentence completion task). The patients with AOS were consistent in producing substantially fewer segmental errors and less articulatory

groping on trochaic than on iambic target words, demonstrating that the metrical properties of words have a robust influence on articulation at the phonetic planning stage of speech production. The observation that the vulnerability of speech segments to apraxic impairment interacts with word-level prosody is compatible with our nonlinear gestural model of speech motor plans, in which articulatory gestures for vowels and consonants are dominated by the syllabic and metrical structure of an utterance (e.g., Ziegler, 2009; Ziegler & Aichert, 2015; Ziegler, Aichert, & Staiger, 2017). In this model, the vulnerability of each articulatory gesture to apraxic error is weighted by, among other things, the gesture’s position within a particular syllable constituent and within a metrical foot of a phonological word; that is, each gesture inherits the properties of the prosodic unit it pertains to.

Most remarkably, the facilitating effect of regular word stress could, for the first time, also be demonstrated in individuals with PI. Similar to the error pattern of the apraxic speakers, patients with postlexical PIs produced fewer segmental deviations and less phonological searching behavior on trochaic compared to iambic target words. However, unlike dyslexic and aphasic patients who were impaired in realizing the stress patterns of words with irregular stress (e.g., Cappa et al., 1997; Laganaro et al., 2002), the patients with PI examined here did not misstress words.

Prosodic effects on PI have been interpreted as evidence for the availability of prosodic information above the level of the phonological word in the prosodic hierarchy, that is, at the level of segment-to-frame association in phonological encoding (Croot et al., 2010). One suggestion is that, in patients with PI, the spelled out nondefault metrical word forms is more demanding than that of the default forms (e.g., Howard & Smith, 2002; Laganaro et al., 2002).

A syllable-wise analysis of the segmental errors revealed that, in patients with AOS, the first (i.e., unstressed) syllables of iambic words had the highest error rates. This result also replicates data from an earlier study (Aichert et al., 2016). Obviously, the initiation of iambic words imposes particular demands on apraxic speakers. Independent from word stress, difficulties in initiating speech have often been reported for patients with AOS (e.g., Aichert & Ziegler, 2004b, 2013; Canter, Trost, & Burns, 1985). They may be explained by higher articulatory demands for word onset compared to word-medial or word-final consonants. For example, Krakow (1999) assumed that onset consonants involve more distinct articulations than word-final consonants. Our results also indicate that unstressed syllables were not per se easier for the apraxic speakers than stressed syllables. This is in contrast to an earlier study, which reported a prevalence of errors on stressed syllables in patients with AOS (Odell, Rosenbek, & Hunter, 1991). Obviously, in our experiment, the impact of a word’s metrical pattern on segmental accuracy outweighed potential syllable-related factors, such as syllable position or syllable weight. In this study, patients with PI did not show any difference in the error rates, depending on syllable position (for a similar result, see Canter et al., 1985). Therefore, the

AQ10

susceptibility to failure at word onsets in patients with AOS may also be exploited as a clinical marker to differentiate these two populations (see also Croot, 2002).

Compared to the auditory prime effect, the target effect was much more pronounced in both patient groups. Whereas the prime effect was confined to segmental error rates, the target effect was also observed for searching behaviors. Therefore, the metrical structure of the output turned out to be more important for phonological and phonetic planning than the metrical structure of the input. This result is not surprising, because both patient groups are considered to suffer from output disorders and are therefore particularly sensitive to the structure of the output itself.

One might ask why there was no effect of the regularity of either the prime or the target on prosodic errors in this study. As an explanation, one might mention that single word production by itself does not provide much space for prosodic errors. However, acoustic analyses might reveal small effects that were not accessible to the perceptual analysis performed here. Acoustic measures of target word production and measurements of response delays in sentence completion will be the subject of a separate report.

Clinical Implications

The effect of the speech rhythm of target words and perceived phrases on accuracy may be exploited in the treatment of sound production impairments, because it entails a potential to modulate therapeutic task demands in a natural way. Whereas there are a number of treatment methods for patients with AOS relying on rhythm-based methods, such as finger tapping or metronome speaking (e.g., Dworkin et al., 1988; Square et al., 2001), there is, to our knowledge, no treatment method so far that systematically exploits the rhythmic structure of speech stimuli. The strong target effects observed here and in earlier studies support the idea that training stimuli with a regular stress pattern may enhance accuracy of articulation and thereby stimulate speech motor learning in patients with acquired speech sound impairments. For this purpose, lists of trochaic words and of phrases composed of trochaic words might constitute valuable treatment materials (e.g., *El-ne LAU-te PAU-ke*, English: a loud timbal). In patients with minor impairments, even poems such as Goethe's "The Sorcerer's Apprentice" could be used to facilitate articulation (Aichert & Ziegler, 2010). Quite similarly, the effect of metrically regular primes demonstrated here might also be exploited in the treatment of sound production disorders. For example, treatment tasks could be designed using carrier phrases with a regular metrical pattern, with the aim of facilitating the initiation and articulation of target words selected for training (e.g., the word "PIZZa" in *HEU-te ESS ich ____*, English: today I will eat pizza).

Conclusion

Although rhythm-based methods have a long tradition in the treatment of AOS, the impact of metrical structure

on sound production errors in patients with aphasia and AOS has been widely neglected. In this study, we found evidence for a facilitation effect of metric regularity of both auditory primes and target words in patients with AOS. The same effect also occurred in patients with PI. Both patient groups were sensitive to the rhythmic structure of auditory prime sentences and showed facilitating effects on speech production after metrically regular primes. Furthermore, our study confirmed earlier results showing that the symptoms of AOS can be modulated positively by a regular (trochaic) stress of words to be produced. We demonstrated here that patients with PI show the same effect; that is, they also benefit from the regularity of target words. Therefore, there seems to be a robust metrical influence on speech at both the phonetic and the phonological planning stages of speech production.

In the approach taken here, patients with acquired sound production impairments were studied in their roles as speakers and listeners at the same time. This research puts itself into the context of self-other approaches in the study of motor cognition (Jackson & Decety, 2004). Given the overall linguistic and speech motor limitations of the patients studied here, the range of options to assess speaker-listener interactions in a controlled experimental setting is restricted. The present approach may therefore be criticized for its lack of ecological validity. Nonetheless, more efforts need to be undertaken to develop new ways to study how phonological and motor impairments are modulated during life interactions with other speakers.

Acknowledgments

The first author received funding from the German Research Council (Deutsche Forschungsgemeinschaft Grant Zi 469/14-2). We are grateful to the patients and to the healthy control speakers for their participation. We also would like to thank the speech-language teams of 14 collaborating centers where patient examinations took place.

References

- Aichert, I., Späth, M., & Ziegler, W. (2016). The role of metrical information in apraxia of speech. Perceptual and acoustic analyses of word stress. *Neuropsychologia*, 82, 171–178. <https://doi.org/10.1016/j.neuropsychologia.2016.01.009>
- Aichert, I., & Ziegler, W. (2004a). Segmental and metrical encoding in aphasia: Two case reports. *Aphasiology*, 18(12), 1201–1211. <https://doi.org/10.1080/02687030444000516>
- Aichert, I., & Ziegler, W. (2004b). Syllable frequency and syllable structure in apraxia of speech. *Brain and Language*, 88, 148–159. [https://doi.org/10.1016/S0093-934X\(03\)00296-7](https://doi.org/10.1016/S0093-934X(03)00296-7)
- Aichert, I., & Ziegler, W. (2010). Therapie bei chronischer Sprechapraxie. *Forum Logopädie*, 24, 6–13.
- Aichert, I., & Ziegler, W. (2013). Word position effects in apraxia of speech: Group data and individual variation. *Journal of Medical Speech-Language Pathology*, 20(4), 7–11.
- Albert, M. L., Sparks, R. W., & Helm, N. A. (1973). Melodic intonation therapy for aphasia. *Archives of Neurology*, 29, 130–131.

AQ11

- Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX lexical database* (CD-ROM). Paper presented at the Linguistic Data Consortium, University of Pennsylvania, Philadelphia, PA.
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Black, M., & Byng, S. (1986). Prosodic constraints on lexical access in reading. *Neuropsychology*, 3, 369–409. <https://doi.org/10.1080/02643298608252028>
- Boersma, P., & Weenink, D. (2013). *PRAAT: Doing phonetics by computer* (Version 5.3.42) [Computer program]. Retrieved from <http://www.praat.org/>
- Brendel, B., & Ziegler, W. (2008). Effectiveness of metrical pacing in the treatment of apraxia of speech. *Aphasiology*, 22, 77–102. <https://doi.org/10.1080/02687030600965464>
- Butterworth, B. (1992). Disorders of phonological encoding. *Cognition*, 42, 261–286. [https://doi.org/10.1016/0010-0277\(92\)90045-J](https://doi.org/10.1016/0010-0277(92)90045-J)
- Canter, G. J., Trost, J. E., & Burns, M. S. (1985). Contrasting speech patterns in apraxia of speech and phonemic paraphasia. *Brain and Language*, 24, 204–222. [https://doi.org/10.1016/0093-934X\(85\)90131-2](https://doi.org/10.1016/0093-934X(85)90131-2)
- Cappa, S. F., Nespor, M., Ielasi, W., & Miozzo, A. (1997). The representation of stress: Evidence from an aphasic patient. *Cognition*, 65, 1–13. [https://doi.org/10.1016/S0010-0277\(97\)00024-3](https://doi.org/10.1016/S0010-0277(97)00024-3)
- Cason, N., Hidalgo, C., Isoard, F., Roman, S., & Schön, D. (2015). Rhythmic priming enhances speech production abilities: Evidence from prelingually deaf children. *Neuropsychology*, 29, 102–107. <https://doi.org/10.1037/neu0000115>
- Cason, N., & Schön, D. (2012). Rhythmic priming enhances the phonological processing of speech. *Neuropsychologia*, 50(11), 2652–2658. <https://doi.org/10.1016/j.neuropsychologia.2012.07.018>
- Croot, K. (2002). Diagnosis of AOS: Definition and criteria. *Seminars in Speech and Language*, 23(4), 267–280. <https://doi.org/10.1055/s-2002-35800>
- Croot, K., Au, C., & Harper, A. (2010). Prosodic structure and tongue twister errors. In B. Fougeron, M. Kuehnert, M. d'Imperio, & N. Vallée (Eds.), *Papers in laboratory phonology 10: Variation, phonetic detail and phonological representation* (pp. 433–459). Berlin, Germany: De Gruyter Mouton.
- Dalla Bella, S., Białuńska, A., & Sowiński, J. (2013). Why movement is captured by music, but less by speech: Role of temporal regularity. *PLoS One*, 8, e71945. <https://doi.org/10.1371/journal.pone.0071945>
- de Bree, E., Janse, E., & van de Zande, A. M. (2007). Stress assignment in aphasia: Word and non-word reading and non-word repetition. *Brain and Language*, 103, 264–275. <https://doi.org/10.1016/j.bandl.2007.07.003>
- Domahs, U., Wiese, R., Bornkessel-Schlesewsky, I., & Schlewsky, M. (2008). The processing of German word stress: Evidence for the prosodic hierarchy. *Phonology*, 25, 1–36. <https://doi.org/10.1017/S0952675708001383>
- Dworkin, J. P., Abkarian, G. G., & Johns, D. F. (1988). Apraxia of speech: The effectiveness of a treatment regimen. *Journal of Speech and Hearing Disorders*, 53, 280–294.
- Fadiga, L., Craighero, L., Buccino, G., & Rizzolatti, G. (2002). Speech listening specifically modulates the excitability of tongue muscles: A TMS study. *European Journal of Neuroscience*, 15(2), 399–402. <https://doi.org/10.1046/j.0953-816x.2001.01874.x>
- Falk, S., Lanzilotti, C., & Schön, D. (2017). Tuning neural phase entrainment to speech. *Journal of Cognitive Neuroscience*, 29(8), 1378–1389. https://doi.org/10.1162/jocn_a_01136
- Féry, C. (1998). German word stress in optimality theory. *Journal of Comparative German Linguistics*, 2, 101–142. <https://doi.org/10.1023/A:1009883701003>
- Fougeron, C., & Keating, P. A. (1997). Articulatory strengthening at edges of prosodic domains. *The Journal of the Acoustical Society of America*, 101(6), 3728–3740. <https://doi.org/10.1121/1.418332>
- Hayes, B. (1995). *Metrical stress theory. Principles and case studies*. Chicago, IL: University of Chicago Press.
- Howard, D., & Smith, K. (2002). The effects of lexical stress in aphasic word production. *Aphasiology*, 16, 198–237. <https://doi.org/10.1080/02687040143000546>
- Huber, W., Poeck, K., Weniger, D., & Willmes, K. (1983). *Aachener Aphasie Test (AAT)*. Göttingen, Germany: Hogrefe.
- Jackson, P. L., & Decety, J. (2004). Motor cognition: A new paradigm to study self–other interactions. *Current Opinion in Neurobiology*, 14(2), 259–263. <https://doi.org/10.1016/j.conb.2004.01.020>
- Jarick, M., & Jones, J. A. (2009). Effects of seeing and hearing speech on speech production: A response time study. *Experimental Brain Research*, 195(2), 175–182. <https://doi.org/10.1007/s00221-009-1765-x>
- Kappes, J., Baumgaertner, A., Peschke, C., & Ziegler, W. (2009). Unintended imitation in nonword repetition. *Brain and Language*, 111(3), 140–151. <https://doi.org/10.1016/j.bandl.2009.08.008>
- Keating, P. A. (2006). Phonetic encoding of prosodic structure. In J. Harrington & M. Tabain (Eds.), *Speech production: Models, phonetic processes, and techniques* (pp. 167–186). New York, NY: Psychology Press.
- Krakow, R. A. (1999). Physiological organization of syllables: A review. *Journal of Phonetics*, 27, 23–54. <https://doi.org/10.1006/jpho.1999.0089>
- Laganaro, M., Vacheresse, F., & Frauenfelder, U. H. (2002). Selective impairment of lexical stress assignment in an Italian-speaking aphasic patient. *Brain and Language*, 81, 601–609. <https://doi.org/10.1006/brln.2001.2550>
- Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1), 159–174. <https://doi.org/10.2307/2529310>
- Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, 106(1), 119–159. <https://doi.org/10.1037/0033-295X.106.1.119>
- Levelt, W. J., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, 22, 1–38.
- Liebold, M., Ziegler, W., & Brendel, B. (2003). *Hierarchische Wortlisten. Ein Nachsprechtest für die Sprechapraxiediagnostik*. Dortmund, Germany: Borgmann.
- Maas, E., Gutiérrez, K., & Ballard, K. J. (2014). Phonological encoding in apraxia of speech and aphasia. *Aphasiology*, 28(1), 25–48. <https://doi.org/10.1080/02687038.2013.850651>
- Mainka, S., & Mallien, G. (2014). Rhythmic speech cueing (RSC). In M. Thaut & V. Hoemberg (Eds.), *Handbook of neurologic music therapy*. New York, NY: Oxford University Press.
- Marshall, J. C., & Newcombe, F. G. (1973). Patterns of paralexia: A psycholinguistic approach. *Journal of Psycholinguistic Research*, 2, 175–199. <https://doi.org/10.1007/BF01067101>
- Miceli, G., & Caramazza, A. (1993). The assignment of word stress in oral reading: Evidence from a case of acquired dyslexia. *Cognitive Neuropsychology*, 10, 273–296. <https://doi.org/10.1080/02643299308253465>

- Nickels, L., & Howard, D. (1999). Effects of lexical stress on aphasic word production. *Clinical Linguistics & Phonetics*, 13(4), 269–294. <https://doi.org/10.1080/026992099299086>
- Odell, K., Rosenbek, J. C., & Hunter, L. (1991). Perceptual characteristics of vowel and prosody production in apraxic, aphasic, and dysarthric speakers. *Journal of Speech and Hearing Disorders*, 34, 67–80. <https://doi.org/10.1044/jshr.3401.67>
- Peirce, J. W. (2007). PsychoPy—Psychophysics software in Python. *Journal of Neuroscience Methods*, 152, 8–13. <https://doi.org/10.1016/j.jneumeth.2006.11.017>
- Peschke, C., Ziegler, W., Kappes, J., & Baumgaertner, A. (2009). Auditory–motor integration during fast repetition: The neuronal correlates of shadowing. *NeuroImage*, 47(1), 392–402. <https://doi.org/10.1016/j.neuroimage.2009.03.061>
- Pilon, M. A., McIntosh, K. W., & Thaut, M. H. (1998). Auditory vs visual speech timing cues as external rate control to enhance verbal intelligibility in mixed spastic–ataxic dysarthric speakers: A pilot study. *Brain Injury*, 12(9), 793–803. <https://doi.org/10.1080/026990598122188>
- Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review*, 12, 969–992. <https://doi.org/10.3758/BF03206433>
- Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, 20(3), 403–452. <https://doi.org/10.3758/s13423-012-0371-2>
- Roelofs, A., & Meyer, A. S. (1998). Metrical structure in planning the production of spoken words. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 24(4), 922–939. <https://doi.org/10.1037/0278-7393.24.4.922>
- Rothermich, K., Schmidt-Kassow, M., & Kotz, S. A. (2012). Rhythm's gonna get you: Regular meter facilitates semantic sentence processing. *Neuropsychologia*, 50(2), 232–244. <https://doi.org/10.1016/j.neuropsychologia.2011.10.025>
- Rubow, R. T., Rosenbek, J., Collins, M., & Longstreth, D. (1982). Vibrotactile stimulation for intersystemic reorganization in the treatment of apraxia of speech. *Archives of Physical Medicine and Rehabilitation*, 63, 150–153.
- Schütz-Bosbach, S., Mancini, B., Aglioti, S. M., & Haggard, P. (2006). Self and other in the human motor system. *Current Biology*, 16(18), 1830–1834. <https://doi.org/10.1016/j.cub.2006.07.048>
- Scott, S. K., McGettigan, C., & Eisner, F. (2009). A little more conversation, a little less action—Candidate roles for the motor cortex in speech perception. *Nature Reviews Neuroscience*, 10(4), 295–302. <https://doi.org/10.1038/nrn2603>
- Shane, H. C., & Darley, F. L. (1978). The effect of auditory rhythmic stimulation on articulatory accuracy in apraxia of speech. *Cortex*, 14, 444–450. [https://doi.org/10.1016/S0010-9452\(78\)80071-9](https://doi.org/10.1016/S0010-9452(78)80071-9)
- Simmons, N. N. (1978). Finger counting as an intersystemic reorganizer in apraxia of speech. In R. H. Brookshire (Ed.), *Clinical aphasiology conference proceedings* (pp. 174–179). Minneapolis, MN: BRK.
- Späth, M., Aichert, I., Ceballos-Baumann, A., Wagner-Sonntag, E., Miller, N., & Ziegler, W. (2016). Entraining with another person's speech rhythm: Evidence from healthy speakers and individuals with Parkinson's disease. *Clinical Linguistics & Phonetics*, 30(1), 68–85. <https://doi.org/10.3109/02699206.2015.1115129>
- Square, P., Martin, R. E., & Bose, A. (2001). Nature and treatment of neuromotor speech disorders in aphasia. In R. Chapey (Ed.), *Language intervention strategies in aphasia and related neurogenic communication disorders* (4th ed., pp. 847–884). Philadelphia, PA: Lippincott Williams & Williams.
- Stadie, N., Cholewa, J., & De Bleser, R. (2013). *LEMO 2.0. Lexikon modellorientiert: Diagnostik für aphasie, dyslexie und dysgraphie*. Hofheim, Germany: NAT-Verlag.
- Stahl, B., Kotz, S. A., Henseler, I., Turner, R., & Geyer, S. (2011). Rhythm in disguise: Why singing may not hold the key to recovery from aphasia. *Brain*, 134, 3083–3093. <https://doi.org/10.1093/brain/awr240>
- Sulpizio, S., Spinelli, G., & Burani, C. (2015). Stress affects articulatory planning in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance*, 41, 453–461. <https://doi.org/10.1037/a0038714>
- Thaut, M. H., McIntosh, K. W., McIntosh, G. C., & Hoemberg, V. (2001). Auditory rhythmicity enhances movement and speech motor control in patients with Parkinson's disease. *Functional Neurology*, 16(2), 163–172.
- Tilsen, S. (2011). Metrical regularity facilitates speech planning and production. *Laboratory Phonology*, 2(1), 185–218. <https://doi.org/10.1515/labphon.2011.006>
- Trost, W. J., Labbé, C., & Grandjean, D. (2017). Rhythmic entrainment as a musical affect induction mechanism. *Neuropsychologia*, 96, 96–110. <https://doi.org/10.1016/j.neuropsychologia.2017.01.004>
- Wambaugh, J. L., & Martinez, A. L. (2000). Effects of rate and rhythm control treatment on consonant production accuracy in apraxia of speech. *Aphasiology*, 14, 851–871. <https://doi.org/10.1080/026870300412232>
- Watkins, K. E., Strafella, A. P., & Paus, T. (2003). Seeing and hearing speech excites the motor system involved in speech production. *Neuropsychologia*, 41, 989–994. [https://doi.org/10.1016/S0028-3932\(02\)00316-0](https://doi.org/10.1016/S0028-3932(02)00316-0)
- Wunderlich, A., & Ziegler, W. (2011). Facilitation of picture naming in anomic patients: Sound vs. mouth shape. *Aphasiology*, 25(2), 202–220. <https://doi.org/10.1080/02687038.2010.489255>
- Ziegler, W. (2005). A nonlinear model of word length effects in apraxia of speech. *Cognitive Neuropsychology*, 22, 603–623. <https://doi.org/10.1080/02643290442000211>
- Ziegler, W. (2008). Apraxia of speech. In G. Goldenberg & M. Miller (Eds.), *Handbook of clinical neurology* (88th ed., pp. 269–285). London, England: Elsevier.
- Ziegler, W. (2009). Modelling the architecture of phonetic plans: Evidence from apraxia of speech. *Language and Cognitive Processes*, 24(5), 631–661. <https://doi.org/10.1080/01690960802327989>
- Ziegler, W., & Aichert, I. (2015). How much is a word? Predicting ease of articulation planning from apraxic speech error patterns. *Cortex*, 69, 24–39. <https://doi.org/10.1016/j.cortex.2015.04.001>

AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1: This article has been edited for grammar, APA style, and usage. Please use annotations to make corrections on this PDF. Please limit your corrections to substantive changes that affect meaning. If no change is required in response to a question, please reply “OK as set.”

AQ2: Please check if affiliations were correctly formatted.

AQ3: Here, to avoid biased language, “severely impaired nonfluent aphasics” was changed to “persons with severe nonfluent aphasia.” Please confirm or provide revisions if needed.

AQ4: Please check if section heading levels are formatted correctly.

AQ5: Per APA style, we avoid one-sentence paragraphs. All such instances have been run back into the previous paragraph.

AQ6: Here, “4,2” was changed to “4.2” as deemed appropriate. Please check whether this change is correct.

AQ7: Figure 4 citation was inserted here. Please check if appropriate.

AQ8: Liberman & Mattingly, 1985, is missing from the reference list. Please provide the reference details or remove the reference from the text.

AQ9: Galantucci et al., 2006, is missing from the reference list. Please provide the reference details or remove the reference from the text.

AQ10: Ziegler, Aichert, & Staiger, 2017, is missing from the reference list. Please provide the reference details or remove the reference from the text.

AQ11: Please provide the English translation of this reference.

AQ12: Please provide the English translation of this reference.

AQ13: Please provide the English translation of this reference.

AQ14: Please cite this reference in the text or confirm if it should be deleted.

END OF ALL QUERIES